Software-defined Mobile Ad Hoc Networks with Trust Management

by

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The undersigned hereby recommends to the
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Abstract

In recent years, mobile ad hoc networks (MANETs) have become popular in different areas. In MANETs, mobile nodes can join or leave the network freely. Because of the mobility of nodes and open wireless medium, MANETs are vulnerable to security attacks. In this thesis, we propose a novel framework of software-defined MANETs with trust management. Specifically, we separate the forwarding plane in MANETs from the control plane, which is responsible for the control functionality, such as routing protocols and trust management in MANETs. Using the on-demand distance vector routing (TAODV) protocol as an example, we present a routing protocol named software-defined trust based ad hoc on-demand distance vector routing (SD-TAODV). Simulation results are presented to show the effectiveness of the proposed software-defined MANETs with trust management.

To my parents and supervisor.

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List of Abbreviations

AODV	Ad Hoc On-demand Distance Vector Routing
CLI	Command Line Interface
DSDV	Destination sequenced distance vector
DSR	Dynamic Source Routing
DARPA	Defense Advanced Research Projects Agency
LLC	Logic Link Control
MAC	Media Access Control
MANETs	Mobile Ad Hoc Networks
NOS	Network Operating System
OLSR	Optimized Link State Routing

QoS	Quality of Service
RREP	Route Reply
RREQ	Route Request
RRER	Request Error
SDN	Software-defined Networking
SD- TAODV	Software-defined Trust based On-demand Distance Vector Routing
T-RREP	Trust Route Reply
T-RREQ	Trust Route Request
WRP	Wireless Routing Protocol

Chapter 1

Introduction

1.1 Research Overview

With the rapid development of network technologies, network scales continue to expand. Meanwhile, as the rapid innovation of Internet services, computer networks have been widely used in various fields, such as military, science, education, and business. People can communicate with each other and can get information from websites through the computer networks. Computer networks profoundly impact people's learning, work and life. However, since the emerging network technologies such as Internet of Things and software-defined networking have been adopted in different areas, the computer networks gradually come out many limitations [2].

In the TCP / IP architecture, network devices (such as switches, routers, etc.) are generally composed of control planes and forwarding planes [3]. The control planes are responsible for forwarding strategies based on gateway protocols and routing protocols. Forwarding planes comprise the entities to execute control logic from the control planes. The main responsibilities of the forwarding plane include data encapsulation, package de-encapsulation, and packet transmission [4]. However, the control planes and forwarding planes in traditional networks are all concentrated

on the network devices. This characteristic makes users difficult to personalize the network according to the various requirements. The tight coupling of the control plane and the forwarding plane result in a series of problems, especially the users hard to manage and adjust the network. [5].

In order to solve these problems, software-defined networking (SDN) has been first introduced by the Clean Slate research group at Stanford University [6]. Software defined networking is an emerging network architecture where network control is decoupled from forwarding plane, and it is directly programmable [7]. Due to the separation of the control planes and the forwarding planes, network nodes only act as forwarding devices and network control logic moves into a logic centralized controller or a networking operating system [8]. On the other hand, depending on the network scale, the control plane may have more than one controllers. If multiple controllers are deployed, a high-speed and reliable distributed network control mechanism can be formed in the peer-to-peer manner. In a word, no matter with either centralized or distributed organizing schemes of the controller, network nodes in the forwarding plane simply forward data through checking flow table(s) that are managed by the controller(s) in the control plane. SDN provides a cost-effective networking approach that aims to reduce the cost of wireless networks and improves the network performance.

On the other hand, with the miniaturization of mobile end devices, mobile ad hoc networks (MANETs) [9] become popular in wide range of fields. For example, they can be used in military, catastrophes, expeditions and so on. Meanwhile, researchers propose higher requirements for MANETs in recent years.

MANETs are evolved from US defense advanced research projects agency (DARPA) [10], which was a wireless network technology branch in the US Department of Defense in the 1970s. DARPA was mainly used in the military field [11]. The

high mobility feature of MANETs enables its wide applications, and thus the research on MANETs attracts much attention from researchers at the United States California Polytechnic State University, Los Angeles adaptive wireless mobile lab, "University of Maryland" Mobile Computing, and multimedia laboratory, etc. [12].

The self-organizing feature of MANETs indicates that no inherent communication network infrastructure is required. MANETs can quickly form temporary networks and establish network communications. In the case that the network infrastructures are seriously damaged by disasters, such as floods, earthquakes, and typhoons, MANETs become the proper method to establish network communications.

However, the distributed network topology, the network node mobility and the wireless channel variation result in performance fluctuation of MANETs, and thus the network control becomes a key challenge. In addition, various node hardware and software configuration may introduce further network control and management complexity.

MANET routing protocols are generally either table-driven routing protocols or on-demand routing protocols [13]. Destination sequenced distance vector (DSDV) [14] is one of the table-driven protocols, and ad hoc on-demand distance vector routing (AODV) [15] is a typical on-demand routing protocol of MANETs. The main objective of those protocols is to find the shortest data forwarding paths from source to destination.

We can use similar techniques as in SDN to solve MANET problems. In this thesis, with the recent advances in SDN, we propose a novel framework of software-defined MANETs with trust management. Specifically, we separate the forwarding plane in MANETs from the control plane, which is responsible for the control functionalities, such as routing protocols and trust management in MANETs. As AODV [16] protocol is frequently used in MANETs, we utilize AODV as an example to implement our

proposed SDN-base framework in MANETs. In addition, we move the AODV control logic and the trust management into the control node. Simulation results demonstrate that our software-defined trust based ad hoc on-demand distance vector routing (SD-TAODV) can improve the network performance significantly.

1.2 Related Background

1.2.1 Mobile Ad Hoc Networks

The concept of MANETs was originated from ALOHA proposed in the 1960s and the “wireless packet data network (PRNET)” project of DARPA [17], and then many projects such as the “viable adaptive network” and the “Global Information System (GloMo)” pushed the MANET development into a new step [18]. Until the 20th century, self-organizing networks were applied in the civilian system.

MANETs are special kind of networks composed of many mobile terminals, which have wireless transceiver capabilities. This class of networks does not need to rely on network infrastructures to quickly implement networking and communications. Wireless links between different nodes can communicate directly or indirectly to complete the information exchange.

The main features of MANETs are concluded in below [19] [20] [21]:

- The variation of network topologies: Most of the wireless networks have been used in the mobile environment. Specifically, the mobile nodes in MANETs can cause the entire network topologies constantly to change. Thus MANET routing protocols, security policies and other MANET technologies should adapt to the variation of topologies of MANETs.
- The security of MANETs is not very reliable: Comparing with the fixed telecommunication networks, nodes in MANETs can dynamically join and leave

the networks at any time. Thus the node mobility feature enables the MANETs more vulnerable to be attacked, such as eavesdropping and intrusion. The MANET security issue is one of the important aspects in ad hoc network researches.

- Self-organization: MANETs can automatically form self-organized networks without individuals' intervention. Meanwhile, node can automatically reorganize when MANETs encounter errors or node failures.
- Multi-hop routing: Each node in MANETs is independent because of the limited communication distance, thus the communication between two non-neighbor nodes needs to implement multi-hop routing. In other words, if a node is outside of the effective range of communication needs to forward packets, this node must go through intermediate nodes to complete the routing path. This mechanism is called multi-hop routing.
- Communication distance is limited: Since each node in MANETs is self-existent, there is no fixed centralized control, together with the energy restrictions of each independent terminal node, all these characteristics make the transmission power of each node in MANETs small, so that the network nodes in an isolated geographical position are not able to communicate with each other.
- Effective network time is limited: Since MANETs often build communications because of some temporary reasons, thus the existence time cycles of entire MANET environment are short, so MANETs cannot maintain stable wireless network environment for a long time.

1.2.2 Software-defined Networking

Since the individuals' demands continue to increase, the requirements of network equipment to meet the individuals' needs become higher and higher. Meanwhile, the increasing complexity of network equipment not only greatly improves the operation and maintenance costs, but also hinders the innovation of network devices. Due to current situations, researchers propose a novel network structure called SDN.

The thought of SDN aims to propose a new network technology in order to break through the limitations of traditional TCP / IP structure. SDN concept is better able to adapt to the rising technologies compared with the traditional networks. Dr. Martin Casado had proposed Ethane architecture [22] that used a centralized controller to send instructions to other network devices in enterprise networks. This mechanism completely controls and manages network resources. Inspired by this project, Professor Nick Mekeown found that the data planes and control planes of conventional network devices are separated from each other using a centralized controller and standardized interfaces for control and management of network devices. This method can provide a more flexible way for network management and can vigorously promote the performance of networks. In 2008, they proposed OpenFlow protocol [23], the core technology of OpenFlow is that it separates the forwarding planes from the control planes of traditional network equipment. In other words, OpenFlow protocol operates through a centralized controller and standardized interfaces to manage and configure a whole network. This thought established the prototype of SDN [24].

SDN can be considered as an emerging network architecture, which has been jumped out of the traditional network hardware restrictions. SDN can quickly adjust, expand and upgrade the network infrastructures. When deploying new services, network devices do not have to be configured individually. It is possible to reduce the time to build and deploy the new services, so SDN improves the network utilization

effectively.

1.3 Thesis Contributions

As we mentioned before, there are many factors that significantly influence the MANET performance. This thesis mainly focuses on the software-defined mobile ad hoc networks with trust management in order to improve MANET performance. We first introduce the main features of SDN and MANET technologies, and then we propose a MANET trust model and an idea of the combination method of SDN and MANETs. Finally, we discuss the simulation results. The main contributions of this thesis are summarized as follows:

- With the recent advances in SDN, we propose a novel software-defined trust based mechanism in MANETs. Specifically, we separate the forwarding plane in MANETs from the control plane, which is responsible for the control functionalities, such as routing protocols and trust management in MANETs. As AODV [15] is one of the most popular routing protocols in MANETs, we use AODV as an example to implement our proposed SDN-base framework in MANETs called SD-TAODV.
- We divide the SD-TAODV into three layers, including MANET network layer, network operating system (NOS) and application layers. In addition, we move the AODV control logic and the trust management into the control node. This scheme aims to improve the network flexibility and management.
- We build the SD-TAODV system operating environment to achieve SD-TAODV prototype and test its functionality.

1.3.1 Accepted and Submitted Papers

The following paper has been accepted:

1. Dajun Zhang, F. R. Yu, and Zhexiong Wei, “Software-defined Vehicular Ad Hoc Networks with Trust Management,” in *Proc. ACM on Design and Analysis of Intelligent Vehicular Networks and Applications (DIVANET’16)*, Malta, Nov. 2016.

The following paper has been submitted:

1. Dajun Zhang, F. R. Yu, and Zhexiong Wei, “Software-defined Vehicular Ad Hoc Networks with Trust Management,” submitted to *Ad Hoc and Wireless Sensor Networks Journal*, Sept. 2016.

1.4 Thesis Organization

The rest of the dissertation is organized as below:

- Chapter 2: In this chapter, entitled “Overview of MANETs and SDN”, we first describe MANETs and its key technologies, including theory and characteristics of the architecture; Meanwhile, we simply depict some representative MANET routing protocols. Secondly we introduce SDN and its northbound and southbound API; then we describe the OpenFlow key technologies, including standard protocols, controllers, and switches information exchange, matching flow table.
- Chapter 3: In this chapter, entitled “MANET Routing Problems and Related works”, we describe the problems of MANET routing protocols. And then we introduce some recent works about the trust based MANET routing protocol mechanism.
- Chapter 4: In this chapter, entitled “Trust Based AODV Routing Protocol (TAODV)”, we describe the AODV routing protocol in detail, and then we

present the route discovery and route maintenance process of our proposed TAODV mechanism.

- Chapter 5: In this chapter, entitled “Software-defined Mobile Ad-hoc Networks based on TAODV”, we detailedly describe fusion method of SDN and MANETs. First we describe the separation of the control and forwarding logic, and then we introduce the working process of controller. Finally the working process of forwarding node is presented in the last part of this chapter.
- Chapter 6: In this chapter, entitled “The Simulation Results and Discussions”, we simulate our proposed scheme, and evaluate the simulation results. The simulation results show that our proposed SD-TAODV system can improve the network performance significantly.
- Chapter 7: This chapter summarizes the conclusion of the thesis and highlights the next step for future works.

Chapter 2

Overview of MANETs and SDN

SDN is seen as a novel network architecture, which changes the traditional network frames, applications and managements. In order to get rid of the restrictions on network hardwares, SDN can easily adjust, expand and upgrade to the network frame. For the MANETs, there are also network control and management issues, so we can refer SDN technology to optimize the network control and management of MANETs.

2.1 Key Technologies of Mobile Ad Hoc Networks

2.1.1 Ad Hoc Theory and its Characteristics

After decades of development, ad hoc networks have gradually developed a theoretical system. MANETs use inherent mechanisms to form complete and complex self-organized systems. There are some rules that need to be followed as the network running: 1) each node in the networks has a criterion for the whole network; 2) each node has its own capacity to implement decisions; 3) each node determining their own behaviors will also affect the state of whole networks; 4) all nodes in the networks operate in the form of parallel [25].

Each node in MANETs can act as a router or a host, which means that either a

node can run as a host to operate user-oriented applications, or it can run as a router to operate the routing protocols such as AODV and DSDV. Meanwhile, nodes can forward packets and operate routing maintenance according to the routing policies.

Ad hoc applications are mainly related to its own characteristics. Compared with the conventional wireless network communication environments, MANET application fields mainly show its self-organization, rapid deployment, and dynamic topology features [26] [27].

- Military: Ad hoc nodes have the features of rapid networking and high mobility, so MANETs are frequently utilized in the military field. Nowadays, soldiers, military vehicles and large equipment are all required to maintain real-time contacts. However, because of the special natures of the battlefields, the battlefields are difficult to build fixed wireless communication environments, so the ad hoc networking is a kind of preferred wireless networks for commanders to establish communications.
- Sensor networks: Sensor networks are mainly used in wireless communication, but due to the small power of the sensor itself and some other reasons, the sensor networks can use ad hoc technologies to form multi-hop mechanism to complete the communications. The combination of MANETs and sensor networks has a very good prospect in the future.
- Disaster environments: When happening some devastating natural disasters such as earthquakes and floods, the existing fixed communication devices cannot complete the communications, so individuals need to quickly establish networks for communications to execute the rescue works. Ad hoc networks enable people to quickly build good communication network environments in such disaster sites.

- Establishing networks in remote areas: When staying in some remote areas, people have to face an environment of non-fixed wireless network infrastructures. If individuals need to build networks, they can take advantage of ad hoc networks to rapidly deploy the efficient wireless communication environments.
- Personal communication applications: Nowadays, PAN (Personal Area Networking) attracts more and more individuals' attention. In order to freely communicate between personal devices and to solve the energy consumption of personal communication devices, people need to establish a wireless communication environment that uses multi-hop ad hoc mechanism to meet the communication needs of individuals.
- Combining with the traditional wireless networks: Ad hoc networks can combine with the traditional fixed network environments. Traditional wireless communication networks can maintain high quality communication environments over a wide range area for a long time, and ad hoc technologies can further expand the local areas of communication networks. The functionality of multi-hop can extend the effective communication distance of traditional wireless networks.

2.1.2 The System Architecture of Mobile Ad Hoc Networks

According to the characteristics of MANET and the traditional TCP / IP structure, we also divide the MANET structure into five layers:

Application layer: Application layer includes different kinds of the functions such as real-time operation and data traffic.

Transport layer: The transport layer operates the TCP and UDP.

Network layer: The network layer includes two sublayers: network interconnected layer and network layer. The network interconnected layer operates IPv4 or IPv6. The network layer is used to operate routing protocols of MANETs.

Figure 2.1: The MANET routing protocols [1].

Data link layer: The data link layer can be divided into two sublayers: logic link control (LLC) layer and media access control (MAC) layer. The data link layer is responsible for data frame detection, packets confirmation and error control. In this thesis, we use IEEE 802.11 as our protocol of MAC layer.

Physical layer: The main technologies of physical layer are phys frequency selection and detection, modulation and demodulation, etc.

2.2 The Categories of MANET Routing Protocols

MANETs require routing algorithms to adapt to their unfixed network topology feature in order to avoid ring paths and to reduce overhead. This requirement makes the network nodes have a ability to justice the current state of the networks. According to the route discovery strategy, MANET routing protocols can be divided into two categories: proactive routing protocols and on-demand routing protocols as shown in Figure 2.1.

2.2.1 Proactive Routing Protocols

In the proactive routing protocols, each node maintains its own routing table, which contains the routing information from one node to other nodes. Nodes periodically broadcast routing information packets to exchange routing information in order to maintain their own routing table. The routing table is updated periodically. When a node needs to send a packet, it can quickly find appropriate routing path(s) according to the routing information in the routing table. One of advantages of proactive routing protocols is that when an intermediate node needs to build communication with another node, a appropriate routing path always can be immediately found. However, table-driven mechanism also brings some disadvantages. For example, networks are required to spend a lot of overhead to maintain routing tables. This disadvantage results the waste of network resources. This kind of routing protocols mainly include DSDV, WRP, OLSR, and so on.

- DSDV

DSDV [28] [29] (Destination Sequenced Distance Vector) protocol is modified through the existing routing protocol RIP. DSDV protocol adapts to the ad hoc wireless network requirements. In this protocol, each node maintains a routing table, which has a routing information of all neighbor nodes connected to this node. One of the routing entries includes: *destination node, hop count, next hop node and sequence number*. Specifically, sequence number is used to justice whether the routing message is the outdated information and to prevent routing loops. DSDV has common features of distance vector routing protocol, it periodically updates routing information. Therefore, DSDV has slow convergence, but unlike other routing protocols, DSDV introduces a sequencing mechanism in order to prevent routing loops, thereby reduces the load of routes, so that

route convergence time has certain reduced. In DSDV, if a network is large-scale, the network overhead is enormous. Similarly, DSDV does not appropriate for the fast-moving network environment.

- WRP

WRP [30] [31] (Wireless Routing Protocol) is a kind of proactive routing protocol. Each node in WRP must maintain four tables: *routing table*, *distance table*, *link cost table* and *message retransmission list*, *routing table* records the destination information, predecessor information and subsequent node information, this recording precursor and subsequent information mechanism effectively prevent routing loops. *Distance table* records the distance from each node to the destination via the intermediate nodes, and the table also contains the next hop information. *Link cost table* records the cost of each node to its neighbors. *Message retransmission table* records the information about retransmission message, which includes *sequence number*, *the times of retransmission*, *ACK flag*, and *updating message list*. A node communicates with its adjacent nodes periodically. The node communication includes routing tables updating and link information exchanging. This mechanism obtains the status of neighbor nodes so that nodes can maintain their own routing table. If adjacent nodes do not send packets or update messages, the nodes send Hello messages to ensure connectivity. In WRP protocol, each node stores information of its neighbors, so any node in WRP can establish relative optimize paths. However, since each node in WRP protocol needs to maintain four information table, WRP requires more memory and needs to maintain additional information, which means the greater network overhead.

- OLSR

OLSR [32] [33] (Optimized Link State Routing) protocol is optimized from the traditional LS (Link State) protocol. OLSR aims to adjust the ad hoc wireless network requirements. In this protocol, each node periodically exchanges information with its neighbors in order to maintain network topology. The key concept of OLSR is multi-point relays (MPR), which reduce the scope of the flooding. Each node selects part of its neighbors as the multi-point relay nodes. When a node sends control packets to all its neighbors, only its MPR nodes forward control packets, and the other neighbor nodes are not able to forward the packets. Thus, the MPR mechanism reduces the number of network packets forwarding, and it can effectively decrease the flooding.

In summary, proactive routing protocols exchange routing information periodically and maintain network topology and routing information, thus the route discovery delay is small. However, proactive protocols need a lot of packets, which means that the protocols enlarge the network overhead. So the proactive protocols are not suitable for the situation that the network topologies always change. In other words, the network control information in this situation will exponentially increase, so that makes the network overhead increase significantly.

2.2.2 On-demand Routing Protocols

Reactive routing protocols [34] [35] also known as the on-demand routing protocols, nodes running at this kind of protocols need to find and establish the routes only when the nodes have demands for transmitting data. This kind of protocols is different from the table-driven routing protocols. Reactive routing protocols do not require to exchange the routing information periodically. Generally, this kind of protocols includes route discovery process and route maintenance process. When a source node sends a packet, and the node routing table does not have a route to destination,

the source initiates the route discovery process. The source node broadcasts request packets to the whole network topology. When the route request packets arrive at the destination node, the valid route is established. The destination node sends a route reply packet to the source in order to establish a forwarding route. The source node then transmits data packets along the established routing path. If the path breakdown, the source node initiates the route maintenance process to restore the route. The features of the reactive routing protocols determine that the network overhead is small, but latency is large. This kind of protocols is not suitable for real-time needs. Reactive routing protocols include DSR, AODV, TORA, etc.

- DSR

The feature of DSR (Dynamic Source Routing) protocol [36] is the source routing mechanism, which means that packet headers contain the routing information about source node to destination node, nodes in DSR send packets according to the packet header information. DSR includes route discovery and route maintenance process. When a node needs to send data packets, first it checks its own routing table whether exists a route to the destination node. If so, source transfers data packets as usual. If not, source initiates the route discovery process. The source node uses flooding method to broadcast route request packets (RREQ), when a node receives a RREQ packet, it first determines whether it receives the same RREQ before, if so, the node discards this RREQ packet; if not, it determines whether the current node is the destination. If this node is the destination, it returns a route reply packet (RREP); if not, the node checks its own routing table if there is a route to the destination node. If the available routes exist, the node responds a RREP packet; if not, the node continues to broadcast the RREQ packet to its neighbor nodes. If a routing path break down, the source node initiates the route maintenance processes. The features

of DSR ensure a loop-free routing path, and nodes only need to maintain the routing information of their connected nodes, rather than the whole network routing information. This mechanism reduces the network overhead, but the head of the data packet must carry the entire route information, which makes the data packet overhead become large. Meanwhile, the flooding method of the route request packets may result unnecessary network overhead.

- TORA

TORA [37] is a distributed routing algorithm. When the network topology changes, a control packet is positioned within the range of the local network topology, so that nodes maintain routing information only with their neighboring nodes. In addition, except for the route discovery and route maintenance process, TORA routing protocol also includes the route removal process, in which uses flooding manner to broadcast CLR (clear) packets to remove the invalid routes. TORA mechanism is more like the process of water flowing from the top of mountain to the foot of the mountain through the pipeline. Data packets or control packets like the water; pipeline like the links between the nodes; each connection point between the pipes are the same meaning with the nodes in the network. Each node in the routing algorithm calculates a height to control the Packets flow from "high" to "low". The CLR packet that has a relatively high value is forwarded to a node having a relatively low value. When a node detects a link broken, the node improves their height values to a more higher level than the height of its neighboring nodes so that makes the "water" reverse, thus makes the "water" flow to the destination node through other routes. The algorithm can find multiple routes from the source node to destination. TORA protocol has strong adaptive ability, high efficiency, and the good scalability, these features make it more suitable for high-speed, dynamic

topology, and multi-hop wireless networks.

From the several representative reactive routing protocols, this kind of routing protocols do not maintain the network topology continuously. They do not maintain the entire network routing information, and only maintains the routing information that the nodes required to build communication. This feature reduces network overhead, but the delay of the on-demand route discovery greatly increases.

2.2.3 AODV Routing Protocol Introduction

AODV is one of the most widely used routing protocols in MANETs [16]. A unique characteristic of AODV is that the routing protocol introduces “sequence number” concept, which is utilized to avoid the *count to infinity* problem and to prevent routing loop [38]. Specifically, each node in AODV must maintain its own routing table that includes routing information about its neighbor nodes. The operating procedure of AODV can be divided into two main operations: route discovery and route maintenance [39].

Route discovery process is initiated by a source node if the source node needs to send data packets to a destination, but there are no valid routes in the routing table of the source node. So the source node first broadcasts RREQ packets to its neighbors. A RREQ packet contains the following fields: *originator IP address, originator sequence number, destination IP address, destination sequence number, and hop count* [16]. There are two different situations when a node receives a RREQ packet: i) this node sends a RREP packet if the node is the destination or it knows the route(s) to the destination; ii) the receiving node establishes a reverse route to the source if the routing table of this node does not have a routing entry to the destination. Figure 2.2 shows the frame of a RREQ packet.

Type: Type field represents the frame type. RREQ frame is set to 1.

Type(8 bit)	J	R	G	D	U	Reserved (11 bit)	Hop Count (8 bit)
RREQ ID							
Destination IP Address							
Destination Sequence Number							
Originator IP Address							
Originator Sequence Number							

Figure 2.2: The frame of the RREQ packet.

J: *J* tag is used to add a tag to achieve multicast reservation.

R: Repair tag is used for the realization of multicast reservation.

G: Gratuitous RREP flag is used to justice whether it generates a free RREP mark to the destination node. If an intermediate node responses RREQ, *G* flag sends a RREP frame including this node IP address to the destination at the same time. This RREP frame is named free RREP frame.

D: It points out that only the destination node can respond to this RREQ.

U: It is used to identify unknown sequence number.

Reserved: Sent as 0; ignored on reception.

Hop Count: The number of hops is calculated by a RREQ packet from the source node to the destination node.

RREQ ID: The ID of RREQ frame.

Destination IP Address: The IP address of the destination.

Destination Sequence Number: The sequence number of the destination node. Each node updates its own sequence number if it receives a better sequence number.

Originator IP Address: The IP address of the source node.

Originator Sequence Number: The sequence number of the source node.

After RREQ packets arrive at the destination, destination node unicasts a RREP packet to the source node along the selected reverse path. The RREP message includes the following fields: *hop count*, *destination IP address*, *sequence number*,

Type (8 bit)	R	A	Reserved (9 bit)	Prefix Sz(5 bit)	Hop Count (8 bit)
Destination IP Address					
Destination Sequence Number					
Originator IP Address					
Lifetime					

Figure 2.3: The frame of the RREP packet.

lifetime, and originator IP address [40]. Figure 2.3 shows the RREP packet frame. When an intermediate node receives the RREP message, it sets up a forwarding route entry to the destination, and continues to send this message to next hop. This procedure will continue until the RREP packet arrives at the source node. When the source node receives the RREP message, the route discovery procedure end, and then data packets are sent to the destination by the source node along the forwarding route entry direction. Figure 2.4 shows the route reply process.

Type: Type field represents the frame type, RREP frame is set to 2.

R: Repair mark is used for multicast reservation.

A: If the RREP information is already set “A”, the nodes which have already received the RREP packets need to return RREP-ACK information.

Reserved: Sent as 0; ignored on reception.

Hop Count: The number of hops transmit from the source node to the destination node.

Destination Sequence Number: The sequence number of the destination node.

Destination IP Address: The IP address of the destination.

Originator IP Address: The IP address of the source node.

Lifetime: The time of a RREP message can be survived in the route discovery process.

Each node in AODV needs to maintain their own routing table, which includes: *destination sequence number, IP address, hop count, next hop and lifetime* [14]. If

Figure 2.4: A route reply process.

the source node wishes to send data packets to the destination, first it needs to check its own routing table whether the routing table has a valid route to the destination. If so, source node sends data packets to its next hop. If not, the source node puts the data packets to its buffer queue and initiates the route discovery process, in which the source broadcasts RREQ packets to its neighbors. When a neighbor node receives a RREQ packet, it updates its routing table and establishes a reverse route to the source. Specifically, each node drops the RREQ packets only if it has already received the RREQ packet with same RREQ ID before. There are two situations that a node responds a RREP message to the source. Either the node is the destination or the node has a fresh route to the destination [41]. Figure 2.5 shows the route discovery process, where S is the source node and D is the destination node, the red lines denote the reverse routes to the source.

The route maintenance procedure is operated by nodes in two different ways. One situation is that a node broadcasts hello messages to its neighbors at regular

Figure 2.5: Route discovery process.

time intervals so that nodes can maintain connectivity with its neighbors. Another situation is that the procedure aims to increase the successful data transmission ratio through the local repair mechanism [38]. Because of the node mobility, a routing path between two nodes maybe breaks, so the local repair aims to recover the routing path. Conversely, if a node do not receive a RREP message during a period of time, the local repair fails and the node sends a request error (RRER) message [38]. A RRER packet contains a list of unreachable destination node information. The functionality of the RRER packet is that the packet can notify the source node to rebuild a new routing path if this source node still needs to transfer data packets.

2.3 Software Defined Networking and its Interfaces

With continuous expansion of the scale of computer networks, routers running on the networks become increasingly complex. In TCP / IP network architecture, network devices (such as switches, routers, etc.) are generally composed of the control and

forwarding planes. The control plane is responsible for the forwarding plane to determine the protocols, which include gateway protocols and routing protocols. The forwarding plane is an entity that operates the routing strategies established by the control plane, including data encapsulation, finding forwarding table, and package de-encapsulation, etc.

However, the control and forwarding planes of network devices are generally designed and developed by the equipment providers. A large number of highly integrated network protocols are concentrated on hardware, and the control planes and forwarding planes are all bundled in the network devices. Configuring and managing the networks are only achieved by people through a command line interface (CLI) [42]. CLI can individually configure a single network device, but CLI is hard for users to control the entire networks because the CLI is not user-friendly, which means that users need to remember a lot of commands and parameters. The users have no other ways to configure and manage the network than typing the complex and right commands. This control and forwarding plane tightly coupled way brings a series of problems in network management and deployment, such as the complexity of network management and low efficiency of the network functions. Therefore, SDN came into our eyes. In recent years, SDN as a future alternative network has attracted more and more attentions.

The framework of SDN is a separated architecture that control and forwarding plane are decoupled from each other. SDN operates through the standardized protocols like OpenFlow to control and manage the network devices [43]. As shown in Figure 2.6, the control plane of SDN is deployed on a controller, the controller intensively control the multiple network devices in network, so SDN improves the network flexibility [44]. Moreover, the control plane has a global view of the network, so SDN allows network administrators to configure the network effectively and to deploy

Figure 2.6: The SDN architecture.

various types of network applications easily.

There are many protocol standards on the use of SDNs in real applications. One of the most famous protocol standards is called OpenFlow [8]. OpenFlow is a widely used protocol that introduces the SDN concepts to implement in hardware and software. An important feature of OpenFlow is that scientists can utilize the existing hardware to design new protocols and to analyze their performance [45].

The frame of OpenFlow can be divided into three layers: network infrastructure layer, control layer, and application layer [46]. Infrastructure layer is composed of underlying network devices (such as OpenFlow switch), which are responsible for forwarding data packets. The control layer is the core layer of the OpenFlow framework, which is responsible for maintaining the entire network status, including network topology, node status, and link status information. Meanwhile, the control layer sends the matched flow table(s) to the underlying network devices through the southbound interface (data forwarding plane and control plane interface), as well as provides information to the upper layer through the northbound interface (control

Figure 2.7: The OpenFlow switch and controller interaction using OpenFlow protocol.

layer and application layer interfaces). Application layer can be invoked through the northbound interface in order to communicate with the underlying network resources. Figure 2.7 shows an example of the OpenFlow architecture.

2.4 OpenFlow Key Technology

In order to achieve SDN requirements, academia and industries have made unremitting efforts to put forward a series of new technologies. OpenFlow technology is a model for the realization of SDN because of its technical specifications and scalability. OpenFlow is now widely accepted by researchers. Many network equipment providers, operators and software companies actively involve in the development of OpenFlow standards and a series of technical support for OpenFlow network devices.

2.4.1 OpenFlow Protocol

The structure of OpenFlow has three important components: switches, controllers and flow-entries [8]. An OpenFlow switch at least includes three fields [47]: a) flow table(s), which each flow table has an action field associated with each flow entry; b) a communication channel, which provides links for the transmission of commands and packets between the controllers and switches; c) an OpenFlow protocol, which enables an OpenFlow controller to communicate with routers or switches. The controller can update flow-entries from the flow table(s) and can inform the switches what they can do in next step. In wireless environment, a static controller can be a brain of whole network to establish packet transfer paths. Most parts of the OpenFlow switches support three actions: a) sending flow packets to a port; b) encapsulating the flow packets and sending them to a controller; c) dropping the flow packets.

2.4.2 The Information Interaction of OpenFlow Protocol

The information interaction between OpenFlow switches and controller(s) supports three kinds of messages: controller-to-switch, asynchronous, and symmetric [23]. In version 1.3 of OpenFlow, controller-to-switch messages are shown in Figure 2.8. The most important message in control-to-switch is the *OFPTFLOWMOD* [48], which is used to modify the flow table in the OpenFlow switches.

Asynchronous messages are initiated by switches, the switches are used to update the status information to the controller. Asynchronous messages include four message types as shown in Figure 2.9. In these four asynchronous message, the most critical message is *OFPTPACKETIN* [23], which OpenFlow switches use this message to send packets to controller if the packets cannot be handled by the switches.

Symmetric messages are initiated by OpenFlow switches or routers. The messages include three types as shown in Figure 2.10.

Figure 2.8: The controller-to-switch message.

Figure 2.9: The asynchronous message.

Figure 2.10: The symmetric message.

2.4.3 The Matched Process of Flow Tables

The core processing unit of an OpenFlow switch is flow table, each of the switches includes a flow table, and the switches can communicate with the controller via a secure channel, and the flow table updates via OpenFlow protocol. The OpenFlow switches establish flow table entries to forward data. In the OpenFlow version 1.3, a flow table entry contains six parts: matched fields, priority, counters, instructions, timeouts, and cookie [49].

- Matched fields: OpenFlow 1.3 provides 40 matching fields, including 13 require fields and 27 optional fields. Required fields include [50]: the switch port (*INPORT*), the Ethernet destination MAC address (*ETHDST*), the Ethernet source MAC address (*ETHSRC*), Ethernet type (*ETHTYPE*), IPv4 or IPv6 protocol number (*IPPROTO*), IPv4 source address (*IPV4SRC*), IPv4 destination address (*IPV4DST*), IPv6 source address (*IPV6SRC*), IPv6 destination

Figure 2.11: The matched process of OpenFlow switch.

address (*IPv6DST*), TCP source port number (*TCPSRC*), TCP destination port number (*TCPDST*), UDP source port number (*UDPSRC*), UDP destination port number (*UDPDEST*).

- Priority: priority field is used to indicate the matched sequence of flow entry.
- Counters: to update the matching packets.
- Instructions: to modify the action sets in flow tables or pipeline processing.
- Timeouts: timeouts is used to record the maximum time before flow is expired by the switches.
- Cookie: maybe used by the controller to filter flow statistics, flow deletion and flow modification, and not used when flow tables process packets.

After an OpenFlow switch receives a data packet, the matching process of flow tables is shown in Figure 2.11. The matching process is begin from flow table 0 and until the packet matches the corresponding matched field, and then the action set of this matched field is operated. If data packets cannot find appropriate fields, the packets are discarded or uploaded to the controller to process through the *OFPTPACKETIN* message.

Chapter 3

MANET Routing Problems and Related Works

In this chapter, we simply describe the problems of the existing MANET protocols. Meanwhile, we discuss and review the related works in the literatures about the trust based schemes.

3.1 The Problems of the MANET Routing Protocols

In MANETs, each node is both host and router, exchanging information between the nodes aims to maintain the network topology and routing information. The purpose of MANET routing protocols is to ensure that data packets can be safely and properly transmitted to the destination node. However, the inherent characteristics of ad hoc networks determine that MANETs are easy to be attacked by a variety of credible threats, which affect data packets correct forwarding. In general, the following aspects are the main problems of MANETs [51] [52] [53].

- Routing protocol technologies

The problems of MANET routing protocols are one of important parts in ad hoc network researches. In terms of the routing, the prominent feature is dynamic and distributed network topologies, but this feature is a big challenge to design protocols in MANETs. The existing routing protocols of MANETs may not meet the real-time dynamic feature of ad hoc networks. Consequently, well-designed routing protocols are the arduous tasks for researchers to improve MANET performance.

- Access control technology

In ad hoc networks, each individual node has autonomous mobile features, while the communication range of each node is limited by its own energy and external conditions, so researchers have to design appropriate MAC protocols to resolve channel problems. For example, channel utilization needs to increase and the network end-to-end delay needs to reduce.

- QoS technology

Currently, ad hoc wireless communication resources may not meet the growing communication needs. For example, large-scale data transmission has a high requirements for the bandwidth of the wireless channel. Meanwhile, the transmission delay and transmission speed of MANETs also have corresponding requirements. In order to ensure efficient transmission of massive amounts of data, QoS techniques have been proposed for the efficient information interaction in the ad hoc networks.

- Energy restriction

Each independent node in MANETs is often limited in energy. The limited energy feature has become one of the main problems of MANETs. The energy consumption of mobile nodes makes the nodes' transmitting power decrease,

which results the mobile nodes invalid and affects the network topologies, evenly may cause network paralysis. Therefore, designing MANET routing protocols must take into account the energy consumption of nodes.

- Network security

Comparing with the traditional fixed communication networks, MANETs have the features of node mobility and open links. These features also make MANET safety cannot be well protected. MANETs are easier attacked by attackers, such as eavesdropping, masquerading and other malicious attacks. Meanwhile, nodes freely join or leave the networks make the security maintenance of ad hoc network become more difficult.

- Resource management

Ad hoc network resource management is a very important and difficult technique. On the one hand, in order to guarantee the quality of service of data processing, we need to manage the radio resource efficiently; on the other hand, we have to solve the problem of rapid changing topology of MANETs. Moreover, since the mobile nodes' energy is limited, power management must be a holistic approach in order to obtain reasonable optimization results.

- The network topology management

Ad hoc networks have multi-hop and self-organization characteristics, so there are more potential problems in network management compared with the traditional fixed and centralized control network. For example, the positioning of mobile nodes has a lot of problems; in addition, how to quickly detect the dynamic changing in MANET topologies also needs to be solved. Meanwhile, ensuring rapid responses for the network services are also one of the MANET problems that needs to be solved in the future.

In summary, there are still some problems that need to be solved in MANETs. Specifically, we mainly focus on the two problems of MANETs in our thesis: one is the network security problem, another is the network topology management. The bad behaviors of nodes brings a lot of problems, including data services cannot be sent correctly, bad nodes degrade MANET performance. How to add security mechanisms in the routing protocols to distinguish and to detect the malicious behaviors of nodes is important for MANET to enhance the network performance. Ensuring the reliable delivery of data services has become a major direction of the MANET researches. With further researches, in order to solve this problem, the concept of reliability and credibility of the route have been proposed, and attracts great attention of the domestic and foreign scholars.

3.2 Related Works

In [54], the authors propose two mechanisms: watchdog and path rater, and use these as DSR protocol extension. Credible watchdog mechanisms need to assume that the nodes need to turn promiscuous mode, which has become a basic assumption of trusted based MANET routing protocols. Watchdog identifies misbehavior of nodes and monitors the received packets to get the trust value. Path rater rates the node according to the reliability of nodes. These two mechanisms can effectively find credible path. The results of the watchdog and path rater mechanism are all better than the Intrusion Detection System. However, in this paper, the authors only used the unicast MANETs and does not evaluate the performance of security techniques to other types of attacks.

Protocol ARAN [55] provides a single path routing solution in a safety management environment. It uses pre-defined encryption certificates to provide authentication and non-repudiation services, thus this mechanism ensures the end-to-end

certification. However, ARAN protocol results in a large route discovery delay and overhead.

Protocol [56] adds a simple packet acknowledgment mechanism, which includes PKT and ACK packets. The protocol uses Merkle Hash Tree method to implement the validation work of PKT packets efficiently. After verification at the destination node, the node sends ACK message. Through these mechanisms, the protocol achieved good scalability.

Protocol LTB-AODV [57] mainly considers the types network attack. Each node turns the promiscuous mode, and each node monitors the behaviors of its neighbors. This paper mainly focuses on two types of attacks: black-hole attack and grey hole attack. In this method, the indirect credibility value is obtained by calculating the average recommendation values of neighbors. The protocol uses a fully distributed algorithm, and only uses information within one hop, so this protocol has a very good scalability. However, this protocol requires each node to listen and save almost all its neighbors communication record, the memory overhead of the protocol is big. Meanwhile, the lack of trust maintenance largely affected the performance of the protocol.

Protocol AOTMDV [58] uses a historical behavior of nodes. The authors propose a credible mechanism mainly based on fuzzy logic prediction method. The protocol can find the shortest paths that nodes meet the minimum requirement of the node trust value. In order to maintain trust value, this protocol uses a routing update reporting mechanism, the amount of changing trust value exceeds the threshold will trigger the routing updates.

Many security schemes have been proposed to enhance the MANET performance. The authors of [59] propose a trust based protocol named AER-AODV, which evaluates direct trust with average encounter rates. An algorithm is proposed in [60]

that both calculates the route and node trust value. Amaresh *et al.* [61] introduce a method of jointly considering trust and energy. Jassim *et al.* [14] present a security-enhanced AODV named Reliant Ad hoc on-demand distance vector routing, which allows AODV not only find the shortest paths but also find shortest path that can be trusted. A trust model called forwarding packets is proposed by Li [62] that the model can evaluate the behaviors of neighbors. They present a novel trust mechanism named ad hoc on-demand trusted-path distance vector routing, which is used to discover multiple loop-free path as the trusted path in route discovery.

Chapter 4

Trust Based AODV Routing Protocol (TAODV)

In this chapter, we describe our trust model based on AODV. We assume that if a node in our TAODV protocol broadcasts a packet to its neighbors, the neighbors receive the packet correctly. However, if a node broadcasts multiple packets at the same time, its neighbors only can receive a part of the packets because of some unexpected causes (such as heavy traffic) and malicious attacks (such as black-hole attack and DoS attack). We use a novel concept *forwarding ratio* and node trust calculation process [62] to evaluate our node trust value.

4.1 Trust Value Calculation Process

In this chapter, we describe our trust model. We first introduce the node trust calculation process, and then we illustrate the reverse and forwarding path calculation processes. Thirdly, the objective function of TAODV is described. Finally, we introduce our trust calculation process.

4.1.1 Node Trust Calculation Process

Definition 1(Forwarding ratio): Forwarding ratio is the number of packets received correctly divided by the number of packets forwarded. For example, we assume that a node a sends 120 packets to its neighbor node b , and node b only receives 100 packets because of the packet loss. Meanwhile, node b only can forward 80 packets because of its transceiver capability, so the forwarding ratio of node b to node a is 0.8. The forwarding ratio $R_{ab}(t)$ of node a to node b can be defined by the following formula

$$R_{ab}(t) = \frac{C_{ab}(t)}{T_{ab}(t)} \quad t \leq W \quad (4.1)$$

where $C_{ab}(t)$ represents the number of the packets that a node can correctly forward to its neighbors. $T_{ab}(t)$ denotes the total number of packets that the node received before time t , where W represents the width of the recent time window.

In TAODV, the packets can be divided into two groups: control packets (RREQ, RREP and RRER) and data packets [62]. The control packets play a vital role in TAODV protocol. The control packets (RREQ and RREP) determine the data transfer path, and forwarding ratio of control packets is an important factor to determine the node trust value. The node trust computation is shown in below

$$N_{ab}(t) = \omega_1 CR_{ab}(t) + \omega_2 DR_{ab}(t) \quad (4.2)$$

where $CR_{ab}(t)$ represents the control packet forwarding ratio and $DR_{ab}(t)$ represents the data packet forwarding ratio. $N_{ab}(t)$ denotes the trust value of receiving node b for forwarding node a . ω_1 and ω_2 are two weighted factors ($\omega_1, \omega_2 \geq 0$, and $\omega_1 + \omega_2 = 1$) that determine which forwarding ratio ($CR_{ab}(t)$ and $DR_{ab}(t)$) is more important in the node trust calculating process. Particularly, we assume $\omega_1 = 1$ and $\omega_2 = 0$, which means that the forwarding ratio of any control packet decides the overall node trust

value.

4.1.2 Path Trust Calculation Process

In the route discovery process, when a control packet such as RREQ arrives at a destination node, the routing path from source to destination is computed according to the node trust defined by the section 4.1.1. According to the axiom [63], concatenation propagation of trust does not increase trust, the reverse and forwarding path trust value should not be more than the trust value of intermediate nodes. Meanwhile, since the control packet is a crucial factor to determine the node trust value, we add a new field called PacketTrust (PT) into the RREQ and RREP packet format and denote by PT_{rreq} and PT_{rrep} . Specifically, we set the initial value of PacketTrust to 1. At time t , the trust value of a reverse path P is denoted by $T_P(t)$ and given by the following formula

$$T_p(t) = N_{ab}(t) \times PT_a^{rreq} \quad (4.3)$$

where PT_a^{rreq} means the trust value of PacketTrust field in RREQ packet when a RREQ packet leaves node a .

$$T_p'(t) = N_{ba}(t) \times PT_b^{rrep} \quad (4.4)$$

where $T_p'(t)$ denotes the trust value of a forwarding path. PT_b^{rrep} means the trust value of PacketTrust field in RREP packet when a RREP packet leaves node b .

4.1.3 The Objective Function of TAODV

In our TAODV mechanism, there are two main factors influencing the whole network performance. One factor is hop count, and another is path trust value. Our goal is to evaluate the network performance in three different scenarios: the first one we only consider the path trust factor, the second one we consider both the hop count factor and path trust factor, the third one we only consider the hop count factor. So the objective function of our proposed TAODV protocol is shown in below:

$$F(x) = \alpha x_1 + \beta x_2 \quad (4.5)$$

where $F(x)$ denotes the network performance of ad-hoc networks using TAODV protocol. x_1 denotes the path trust value when control packets arrives at nodes, and x_2 denotes the hop count of control packets. x_1 and x_2 are two influence factors that determine the network performance when using TAODV protocol. α and β ($\alpha, \beta \geq 0$) are two weighted factors.

From this equation, we make three assumptions that help us to analyze the TAODV mechanism:

- When $\alpha \gg \beta$, we assume that the network performance is mainly decided by the path trust value x_1 .
- When $\alpha \approx \beta$, we assume that the network performance is decided by the path trust value x_1 and hop count x_2 .
- When $\alpha \ll \beta$, we assume that the network performance is decided by the hop count. This scenario is same as the original ad-hoc networks using AODV protocol.

4.2 Route Discover Process of TAODV

The traditional AODV protocol aims to select a minimum hop count path to transfer the data packets. By contrast, in our TAODV protocol, we propose a trust based RREQ (T-RREQ) packet format, which contains the following fields:

(RREQID, HopCount, SourceAddr, SourceSeq, DestAddr, DestSeq, PacketTrust)

As mentioned before, we design a new field named PacketTrust (PT), and add it into a RREQ packet. It is initialized to 1 and varies during the packet transmission process.

In our TAODV protocol, when a node receives a T-RREQ packet from its neighbor, first this node checks the *RREQID* of this T-RREQ. If the node has already received the same ID before, this T-RREQ is dropped by this node. On the contrary, if the *RREQID* is new, the routing table of the node checks the sequence number in the RREQ packet, if the sequence number is fresh, the reverse path is established by the node and it updates its own routing table in which calculates the path trust value, if the sequence number is old, the node discards this RREQ packet. Meanwhile, when the node receives the T-RREQ message, it checks its routing table to determine whether this node is destination or have a fresh route to destination. If so, it updates its routing table and responds a T-RREP packet back to the source. If not, the node continues to broadcast this T-RREQ packet to its neighbors. If the node receives the different T-RREQ packets simultaneously, the node chooses a best path in the routing table with better path trust value. In other words, if the new path trust value is better than the previous one, the node updates the routing table immediately. Algorithm 1 depicts the reverse path trust calculation process of TAODV protocol.

Figure 4.5 shows an example of reverse path establishment process of TAODV. We assume that the source node need to initiate the route discovery process. The source

Algorithm 1 Route Discovery Calculation Process of TAODV Protocol

1: Initialization

1: **if** node B receives a RREQ packet from its neighbor node A , and this packet does not be received by node B , then node B calculates the reverse path trust value in its routing table.

2: **end if**

3: **if** node B receives two different RREQ packets from its neighbor nodes C and D , and the two RREQ packets do not received by the node B before, then node B calculates the two reverse path trust values in its routing table.

4: **if** we only consider the path trust value factor, then node B selects the better trust value path, and discard another RREQ packet.

5: **else**

6: **If** we consider the path trust and hop count factors, then node B selects the better trust value and minimum hop count path, and discard another RREQ packet.

7: **end if**

8: **end if**

9: **end if**

Figure 4.1: An example of the TAODV calculation process.

first broadcasts T-RREQ packets to its neighbor node 1 and node 6. Meanwhile, the PacketTrust field in the T-RREQ is set to 1. The T-RREQ packets arrive at node 1 and node 6, the path trust is calculated in (4.3). The path trust value from source to node 1 is $T_{s1} = 0.9 \times 1 = 0.9$. The path trust from source to node 6 is $T_{s6} = 0.7 \times 1 = 0.7$. When node 1 and node 6 receive the T-RREQ packets, the value of PacketTrust field of the T-RREQ packets changes to 0.9. Node 4 receives two T-RREQ packets from node 6 and node 1. The routing table of node 4 compares the path trust value. Here the path trust $T_{64} = 0.7 \times 0.8 = 0.56$ and $T_{14} = 0.9 \times 0.8 = 0.72$. So node 4 discards the T-RREQ packet from node 6 because the path trust value from node 6 to node 1 is smaller than the path trust value from node 1 to node 4. After the path selection, node 4 sets up the reverse paths to the source. Similarly, the final reverse path is from destination, via node 7, node 4, and node 1 to the source.

When receiving a T-RREQ, destination node replies T-RREP back to the source node via the intermediate nodes. Meanwhile, the forwarding paths are established when T-RREP packets pass through the switch nodes. The format of a T-RREP packet contains the following fields:

(SourceAddr, SourceSeq, DestAddr, DestSeq, HopCount, LifeTime, PacketTrust)

After receiving the RREP packet, the source sends the data packets following the forwarding path that established before to the destination node.

Chapter 5

Software-defined Mobile Ad-hoc Networks based on TAODV

In this chapter, we present a novel architecture SD-TAODV for data transmission based on SDN. In the traditional AODV protocol, flow change of transmission packets due to the high node mobility occurs frequently [64]. Control logic and forwarding logic are all concentrated on MANET nodes. By contrast, in our SD-TAODV system, we move the control logic of MANETs from forwarding plane to a control plane in order to improve the network performance.

5.1 Framework Description

The framework of SD-TAODV is similar with the traditional SDN architecture. We divide the structure of SD-TAODV into three layers: (1) data forwarding plane operates the TAODV protocol and nodes in the plane support the OpenFlow protocol; (2) NOS (controller) layer aims to manage the network topology and establishes the data transfer path for the data transmission; (3) application layer controls the forwarding rules, routing tables, and routing protocols. The whole SD-TAODV mechanism virtualizes the MANETs and provides the services for the application layer through the

Figure 5.1: Traditional OpenFlow switches and controller interaction using OpenFlow messages.

OpenFlow interfaces.

Figure 5.1 shows the data transfer process of the traditional SDN architecture. For the original OpenFlow structure, no matter the switches or the controller, they are all fixed. However, the TAODV topology always keep changing because of the node mobility, so the architecture of SD-TAODV should be different from the traditional SDN. As shown in Figure 5.1, the information interaction of the traditional OpenFlow has three types: user devices and OpenFlow switches interaction, switches and OpenFlow controller interaction, and switches' interaction. In the SD-TAODV, as shown in Figure 5.2, node 1 acts as a controller that manages the whole network.

Figure 5.2: An example Mobile ad-hoc network using SD-TAODV mechanism.

There are three different types of information interactions in the SD-TAODV network: controller-to-switch information interaction, control packets interaction, and data packets interaction. For example, controller-to-switch includes control node 1 sends OpenFlow messages to the forwarding nodes (Flow-mod message), and the control packets interaction includes node 2 sends control packets (RREQ or RREP) to node 6.

Figure 5.3 depicts the working process of switches. Briefly, if a switch node receives a TAODV control packet (T-RREQ or T-RREP), it sends the packet to the controller to handle. If a switch node receives a data packet, it forwards the packet to its neighbor node(s). The centralized control mechanism in SD-TAODV manages the whole network in the control node. So the control node first needs to know the whole

Figure 5.3: The working process of switches based on TAODV protocol.

network topology.

SD-TAODV intensively control and manage the entire network through developing the routing strategies, so the control node must have a whole network topology information. So we need to design a message to obtain the entire network topology in NOS layer. The message can be designed by broadcasting node information to the entire network, and then control node can get the topology of the entire network.

In SD-TAODV, if choosing a fixed node as the control node, because of the node mobility, we cannot exclude a situation that the node maybe leaves the network at any time. Therefore, this situation brings a key issue that how to choose a terminal node as a controller for the whole network. One solution is that try to run a control program on each node. Although such programs are relatively simple, they also can bring some problems. For example, the control programs in two neighbor nodes may clash with each other, and how to choose one of the nodes (each node running the

control program) as the controller; another solution is that automatically assigns the best status network node as the control node. The best status node means that the node has the highest forwarding ratio. We can factitiously select the best status node to serve as the controller. Finally, setting a standby control node is necessary because the standby node can quickly restore communication network if the precious control node is lost.

5.2 The Control and Forwarding Logic Separation Method

As we described before, the separation method is to design a mechanism that makes the controller get the whole network topology. The method of discovering the network topology is that the control node sends topology request message to its neighbor(s). The topology request message includes the following fields:

(PacketID, ControllerAddr, NodeTrustList, TopologyList)

The *NodeTrustList* is used to record the trust value of nodes when a topology request message has passed by. When the message arrives at any one of the nodes in the network topology, the *TopologyList* records this node information and adds the information into the *TopologyList* field. Specifically, if a node receives the same *PacketID* request message, the node sends back this packet to the controller immediately. Similarly, one of nodes in the network topology sends the message back to the controller if all of its neighbor nodes have already in the *TopologyList* field. When the control node receives all the responses, the controller can establish the whole network topology or updates the exciting topology. Figure 5.2 shows an example of the TAODV network topology. The method of control node 1 to get the whole network topology is shown in below:

1) Controller 1 initializes the topology request messages (e.g ID is 1357), and adds them into the *TopologyList*. Controller 1 sends the request messages to its neighbors, nodes 2 and 3.

2) Node 2 receives the request packet and adds itself into the *TopologyList*. Meanwhile, node 2 puts its own trust value into the *NodeTrustList*, and then node 2 broadcasts the message to its neighbor, since the *TopologyList* already has the information of node 1, so node 2 only transfers the message to nodes 3,4 and 5. Similarly, node 3 only sends the request packet to its neighbor 6. Meanwhile, node 3 sends the message back to node 2 because the *PacketID* is the same. Node 4 receives the request message from the node 2, and node 4 puts itself into the *TopologyList*. Since node 2 already exists in the *TopologyList*, node 4 only transfers the message to the node 6. Analogously, node 5 also sends the request message to node 6.

3) Node 6 receives the request messages from nodes 3, 4 and 5. First node 6 puts its routing information into the *TopologyList*, and adds trust information into the *NodeTrustList*. Secondly, since the *PacketID* of three packets is the same, so node 6 sends back these three messages back to the controller 1 according to the *ControllerAddr*.

4) When receiving all the responses from other nodes, controller 1 enables to get the whole network topology.

5.3 The Design Method of Controller

The SD-TAODV control node is responsible for the entire network management and control, and the forwarding node supports OpenFlow protocol. OpenFlow protocol used to send messages and resolve.

Figure 5.4: The working process of control node based on TAODV protocol.

5.3.1 The Working Process of the Controller

After getting the network topology, the controller can control and manage the whole network. The information interaction method between the control node and the OpenFlow switches includes the OpenFlow messages such as *OFPTFlowMod*, *OFPTPacketIn* and *OFPTHello*. The interfaces between the controller and OpenFlow switches are similar to the traditional southbound API.

The working process of the control node is shown in Figure 5.4. When receiving an OpenFlow message from a forwarding node, the controller determines the type of the message, if the message is *OFPTHello*, the controller responds the message and builds a connection between the node and controller. If the message is the *OFPTPacketIn*, the control node resolves the message and gets the message information, which includes the details of the T-RREQ and T-RREP packet. As we described before, when a T-RREQ or T-RREP packet arrives at the control node,

the controller gets the value in *PacketTrust* field, and calculates the path trust value. After finishing the packets handling, the controller sends an *OFPTFlowMod* message to the forwarding node.

5.3.2 The Implementation of OpenFlow Protocol in SD-TAODV

As previously described, the SD-TAODV control node and the forwarding node configuration all support OpenFlow protocol. In order to implement OpenFlow protocol in SD-TAODV network, the underlying MANET network layer needs to have appropriate interfaces supported for southbound API.

The MANET network layer is used to transmit and analyze the messages, including *OFPTHELLO*, *OFPTPACKETIN*, and *OFPTFLOWMOD*.

All OpenFlow messages are derived from the same abstract base class *OFMessage*. For example, *OFPTHELLO* message is used to build the connection between the control node and forwarding node. The message contains only the head of protocol. The variables of the *OFPTHELLO* message include: *version*, *type*, *length*, and *transaction*. The *version* represents the protocol version number; *type* depicts the types of the protocol message; *length* represents the total length of the protocol message; *transaction* is used to report a unique number of the *OFPTHELLO* message.

OFPTPACKETIN message for forwarding node is used to request a flow table. The main parts of the *OFPTPACKETIN* include: *bufferID*, *totallength*, *importNo*, *OFPacketReason*, and *PacketData*. Specifically, the *OFPacketReason* field represents the reason why switch nodes request the flow table. The functionality of *PacketData* field is used to forward data.

Figure 5.5: The working process of forwarding node based on TAODV protocol.

The most critical one is *OFPTFLOWMOD* message, which includes the following main variables: *MatchField*, *Cookie*, *command*, *idleTimeout*, *hardTimeout*, *Priority*, *bufferID*, and *Flags*.

All OpenFlow protocol messages are encapsulated in the UDP packets and transmitted to other nodes. The forwarding nodes establish the UDP connection with the control node by monitoring the control node, and then send the encapsulated OpenFlow protocol message to the control node, the control node resolves the message and responds to the forwarding nodes. After the forwarding nodes receive the responses, they follow the instructions to execute the actions.

5.4 The Design of Forwarding Nodes

The forwarding nodes in the SD-TAODV are used to transfer the data packets and control packets. The interfaces between the control node and switches are the south-bound API, which supports the *OFPTHello*, *OFPTFlowMod* and *OFPTPacketIn* messages.

In the SD-TAODV system, the forwarding nodes send the *OFPTHello* messages to the control node periodically. If any node in the network topology receives the response from the control node, this forwarding node builds a connection with the control node. If a forwarding node receives a control packet such as T-RREQ packet from its neighbors, the T-RREQ packet first matches the flow table (we assume that RREQ cannot match the flow table). Otherwise, the forwarding node sends this packet to the controller in order to request a new flow table with the *OFPTPacketIn* message. After resolving the packet, the control node responds an *OFPTFlowMod* message back to the node and modifies the flow table, and executes the action set in the flow table to handle this packet. Figure 5.5 describes the working process of the forwarding node.

Chapter 6

Simulation Results and Discussions

In this chapter, we describe our simulation setup, configuration, and simulation results. OPNET is used as the simulator. In SD-TAODV simulations, we consider two different scenarios in the route discover process: the first one only considers the path trust value factor, and the second one both considers the hop count factor and path trust value. Moreover, in our simulations, we assume that the nodes in our TAODV is all SDN-enabled. In addition, we assume that our SD-TAODV network includes two different types of nodes: i) normal nodes, which the data packets are normally forwarded by those nodes; ii) malicious nodes, which randomly drop the data packets when they receive the packets. The number of the malicious nodes is much smaller compared with the number of normal nodes.

6.1 SD-TAODV Simulation Setup

Our simulation model is built on the OPNET Modeler. We consider three different situations that we described in Chapter 4. In our simulation, We choose the highest forwarding ratio node as the controller, and reverse and forwarding path trust value is calculated by the (4.3) and (4.4). The simulation parameters are as follows:

- 1) Packet size: 1024 bytes

- 2) Transport protocol: UDP
- 3) Network protocol: OpenFlow
- 4) Routing Protocol: AODV
- 5) MAC protocol: IEEE 802.11
- 6) Physical protocol: IEEE 802.11b
- 7) Data rate: 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps
- 8) Simulation area: $5 \times 5 km^2$
- 9) Number of nodes: 10, 13, 16, 19, 22, 25
- 10) Simulation time: 15mins

There are four metrics evaluated in our simulation:

- *Average end-to-end delay*: the average end-to-end delay is the time that is calculated by the data packets to be transferred across the whole network from the source node to the destination node. It includes buffer delays during the route discover process, queuing delays at interface queues, retransmission delays at MAC layers, and the propagation time from the source to the destination [62].
- *Network throughput*: the throughput is the total size of packets received by the destination node at every second. The network throughput is an important factor that evaluates the network performance.
- *Total message sent*: the total message sent is amount of the routing traffic sent in the entire network.
- *Packet delivery ratio (PDR)*: PDR is the ratio of the number of data packets received by a destination node and the number of the data packets generated by a source node.

6.2 Evaluation

Firstly, the average end-to-end delay of the proposed SD-TAODV scheme is evaluated through Figure 6.1 and Figure 6.2. From these two figures, we can see that the end-to-end delay of the SD-TAODV is higher than the traditional AODV with different data rates (1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps). Similarly, Figure 6.3 and Figure 6.4 depict the comparison of the end-to-end delay with the time variation, in which the average end-to-end delay of the SD-TAODV system is still higher than the traditional AODV protocol. The reason why the end-to-end delay increasing as the data rates grow is that the quality of channels becomes more and more bad as the node velocities grow, so the risk probability of packet loss in the channels increases. As the data rates grow, the packets are easier to be dropped in the channels, so the end-to-end increasing as the data rates grow. There are two reasons for the higher end-to-end delay of SD-TAODV: i) in the route discovery process, the SD-TAODV nodes always select fresh and higher path trust value routes to establish reverse and forwarding paths in order to transfer the data packets to the destination. The best trust value route reduces the risk probability of route breakdown because of the drop. However, the new routes may have more hop counts to the destination than the traditional AODV. The data packets need to spend more time to be transferred in the new routes; and ii) for the SD-TAODV scheme, the nodes first need to build connection with the control node. When TAODV packets (T-RREQ, T-RREP) arrive, nodes send the control packets to the controller to handle. This process also needs to spend some time. So comparing with the traditional AODV network, the end-to-end delay of SD-TAODV is higher.

Figure 6.5 depicts the throughput comparison of the SD-TAODV and traditional AODV in different data rates. Through Figure 6.5, we can conclude that the performance of the proposed SD-TAODV mechanism is better than the traditional

Figure 6.1: The average ETE delay of SD-TAODV with trust value in different data rates.

Figure 6.2: The average ETE delay of SD-TAODV with trust value and hop count in different data rates.

Figure 6.3: The average ETE delay comparison of SD-TAODV with the time variation in 5.5 Mbps.

AODV protocol. Specifically, we also compare the network throughput in the case of the 5.5 Mbps and 11 Mbps within the time variation. Figure 6.6 and Figure 6.7 show the network throughput of the SD-TAODV with trust and hop count and the SD-TAODV only with the trust value are both better than the traditional AODV. These two scenarios indicate that the network performance of the SD-TAODV is also better than the traditional AODV network. As the data rates grow, we can see that the throughput of both the SD-TAODV and original AODV all increases. This is because more data packets can be received as the data rates grow. The reason for the better performance of the SD-TAODV is that the best trust value path is selected by the SD-TAODV system, which means that the selected path between two nodes reduces the risk of packet loss and the quality of links are better than the traditional AODV. In other word, as the data packets are transferred on the secure paths, the possibilities of packets loss are lower than the traditional AODV. So the SD-TAODV scheme has performance improvement in terms of network throughput compared to traditional AODV.

In addition, we also evaluate the SD-TAODV network performance in different numbers of MANET nodes. In Figure 6.8, we can see that the throughput of the

Figure 6.4: The average ETE delay comparison of SD-TAODV with the time variation in 11 Mbps.

Figure 6.5: The average throughput comparison of SD-TAODV with different data rates.

Figure 6.6: The average throughput comparison of SD-TAODV with time variation in 5.5 Mbps.

SD-TAODV and original AODV all decreases as the number of nodes grows. We assume that the number of malicious nodes increases as the number of nodes grows. The malicious nodes also have big impact on the throughput of the SD-TAODV network [65]. The network throughput decreases significantly, as shown in Figure 6.8. Although the network throughput decreases as the number of nodes grows, the SD-TAODV network throughput is still better than the original scheme. Because network nodes update their neighbors' information periodically, the control node of SD-TAODV can respond faster to the topology change. As the network nodes leave or join the network, the control node detects the topology change and sends the control message to these new nodes to maintain the data transfer path, which means that the possibilities of links interruption decrease. So our proposed scheme has performance improvement than the traditional AODV.

Meanwhile, we compare the total message overhead sent in different nodes. Figure 6.9 depicts how much message overhead sent by the SD-TAODV mechanism compared with the traditional AODV protocol. Through Figure 6.9, we can conclude that the message overhead of the SD-TAODV is higher than the original AODV. This is because the nodes in the SD-TAODV network need to send extraneous messages such

Figure 6.7: The average throughput comparison of SD-TAODV with time variation in 11 Mbps.

Figure 6.8: The average throughput comparison of SD-TAODV number of nodes.

Figure 6.9: Total message overhead comparison in different number of nodes.

Figure 6.10: PDR versus the number of nodes.

Figure 6.11: PDR versus the node velocity.

as *OFPTHHello* and *OFPTPacketIn* to the control node. In Figure 6.9, since more nodes join the network as the number of node increases, so the message overhead grows simultaneously in both AODV and the SD-TAODV system.

In Figure 6.10, we also compare PDR with different number of nodes. From the Figure 6.10, we can conclude that the PDR of our proposed scheme is better than the traditional AODV scheme. there are two reasons for the higher PDR of the proposed SD-TAODV scheme: i) the reverse and forwarding path trust calculation of our proposed SD-TAODV can detect and reduce the misbehavior of malicious nodes, and ii) the SD-TAODV scheme reduces the possibilities of interruptions of the routing paths. The results also illustrate that the proposed scheme with the hop count factor and path trust value factor has the highest PDR among the three schemes. Through this figure, we also can demonstrate that the PDR of the three schemes are all decrease as the number of nodes grow. This is because that the number of the malicious nodes increases simultaneously as the number of nodes grows, so the misbehavior of the malicious nodes increase the possibilities of packet loss in the three schemes.

Finally, we compare the PDR with different node velocities. In Figure 6.11, as the node velocity increases, the PDR of all three schemes decreases significantly. This is because that the quality of channels becomes more and more bad as the node velocity increases, so the packets are easier to be dropped in the transmission. However, the PDR of the proposed SD-TAODV scheme is still better than the original AODV protocol.

Chapter 7

Conclusions and Future Works

In this thesis, we mainly focused on the trust based MANET routing protocols and SDN technology. We discussed the development, architecture, routing protocols and the problems of MANETs. Meanwhile, We introduced SDN frame and analyzed the main characteristics of SDN, OpenFlow, and its southbound and northbound interfaces. We have presented a novel framework of software-defined MANETs with trust management. We designed a routing protocol named software-defined trust based ad hoc on-demand distance vector routing (SD-TAODV). In the SD-TAODV scheme, the route discovery and the route maintenance process are moved into a controller, and the reverse and forwarding paths are chosen by the controller. Simulation results were presented to show the effectiveness of the proposed software-defined MANETs with trust management. We compared our SD-TAODV protocol with the traditional AODV protocol in terms of end-to-end delay, throughput and message overhead. Although the end-to-end delay and the message overhead of SD-TAODV are higher than AODV, the network throughput performance improves significantly in our proposed SD-TAODV mechanism. The main research works are concluded as follows:

- We summarized MANET concept, development, features, applications and key technologies. On the basis of the current researches, we introduced the ad hoc

network routing protocols. We discussed the existing ad hoc network routing protocol classification method that includes the Proactive routing protocols and reactive routing protocols. We have introduced some examples of these two kinds of routing protocols. We summarized the problems of current ad hoc networks, and concluded the current researches about the trust based MANET routing protocols.

- We simply introduced the concepts and features of SDN and OpenFlow. We have analyzed the OpenFlow architecture, matched process of flow table, and information interaction of OpenFlow. All these features can be used in our proposed SD-TAODV mechanism.
- We have modified the original AODV protocol that adds trust mechanism into our trust model. We referred a forwarding ratio concept to establish our trust model. First we have defined the node trust value and path trust value, and then we described our objective function of TAODV. We considered different situations to evaluate our proposed mechanism.
- We also proposed a new AODV network frame (SD-TAODV). We have combined the SDN concept with the AODV protocol. In SD-TAODV, the route discovery and the route maintenance process are all moved into the control node, in which the reverse and forwarding paths are chose by the control node. Meanwhile, the route maintenance such as local repair is also decided by the controller. In our simulation, each node is given a node trust value based on the forwarding ratio concepts. We compared our SD-TAODV model with traditional AODV in end-to-end delay, throughput and message overhead. Although the end-to-end delay and the message overhead of SD-TAODV are higher than the AODV protocol, the network performance improves significantly in SD-TAODV

system.

In the future, we will aim to reduce the end-to-end delay of our proposed scheme. Meanwhile, in our SD-TAODV, since our controller is a moving node, we wish to design a mechanism that can choose a new control node if the previous controller is lost.

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Appendix A

Simulation Programs

```
1 ]
2
3 This function is used to handle the RREQ packets
4 Function static void
5 aadv\_rte\_rreq\_pkt\_arrival\_handle (Packet* ip\_pkptr, Packet*
6     aadv\_pkptr, IpT\_Dgram\_Fields* ip\_dgram\_fd\_ptr,
7     IpT\_Rte\_Ind\_Ici\_Fields* intf\_ici\_fdstruct\_ptr,
8     AadvT\_Packet\_Option* tlv\_options\_ptr)
9 {
10     AadvT\_Rreq*      rreq\_option\_ptr;
11     InetT\_Address    prev\_hop\_addr;
12     AadvT\_Route\_Entry* route\_entry\_ptr = OPC\_NIL;
13     AadvT\_Route\_Entry* rev\_path\_entry\_ptr = OPC\_NIL;
14     IpT\_Interface\_Info* iface\_elem\_ptr;
15     IpT\_Port\_Info    in\_port\_info;
16     double            min\_lifetime, lifetime;
17     double            nodetrust\_value, pathtrust\_value;
18     double            actrust\_value;
19     int               dest\_seq\_num, new\_ttl\_value;
20     Packet*           ip\_rreq\_pkptr;
21     char             src\_node\_name [OMSC\_HNAME\_MAX\_LEN];
22     char             src\_hop\_addr\_str [INETC\_ADDR\_STR\_LEN];
23     char             dest\_node\_name [OMSC\_HNAME\_MAX\_LEN];
24     char             dest\_hop\_addr\_str [INETC\_ADDR\_STR\_LEN];
25     char             temp\_str [2048];
26     double            existing\_lifetime;
27     AadvC\_Route\_Entry\_State route\_entry\_state;
28     Boolean          dest\_seq\_flag = OPC\_FALSE;
29     InetT\_Subnet\_Mask selected\_subnet\_mask;
30     Ici*              ip\_iciptr;
31     int              mcast\_major\_port = IPC\_MCAST\_ALL\_MAJOR\_PORTS;
32     Manet\_Rte\_Ext\_Cache\_entry* ext\_cache\_entry\_ptr = OPC\_NIL;
```

```

31
32  /** Handles the arrival of a route request message */
33  FIN (aodv\_rte\_rreq\_pkt\_arrival\_handle (<args>));
34
35  /* A route request packet has arrived at this node */
36  /* Get the request options from the packet */
37  rreq\_option\_ptr = (AodvT\_Rreq*) tlv\_options\_ptr->value\_ptr;
38
39  /* Get the previous hop from which this packet arrived */
40  prev\_hop\_addr = ip\_dgram\_fd\_ptr->src\_addr;
41
42  /* The source address needs to be set at the first hop */
43  /* for the route request as when sending out the RREQ */
44  /* from the actual source node, the output interface */
45  /* address is not known as it is broadcast. */
46  if (rreq\_option\_ptr->hop\_count == 0)
47      rreq\_option\_ptr->src\_addr = inet\_address\_copy
          (prev\_hop\_addr);
48
49  if ((op\_prg\_odb\_ltrace\_active ("trace\_rreq") == OPC\_TRUE) ||
      LTRACE\_ACTIVE)
50  {
51      inet\_address\_print (src\_hop\_addr\_str ,
52                          ip\_dgram\_fd\_ptr->src\_addr);
53      inet\_address\_to\_hname (ip\_dgram\_fd\_ptr->src\_addr ,
54                             src\_node\_name);
55      inet\_address\_print (dest\_hop\_addr\_str ,
56                          rreq\_option\_ptr->dest\_addr);
57      inet\_address\_to\_hname (rreq\_option\_ptr->dest\_addr ,
58                             dest\_node\_name);
59      sprintf (temp\_str , "from node %s (%s) destined to node %s (%s)
60                  with request ID (%d)",
61              src\_hop\_addr\_str , src\_node\_name , dest\_hop\_addr\_str ,
62              dest\_node\_name , rreq\_option\_ptr->rreq\_id);
63      op\_prg\_odb\_print\_major (pid\_string , "Received a Route
64      Request", temp\_str , OPC\_NIL);
65  }
66
67  /* Update the connectivity table */
68  aodv\_rte\_neighbor\_connectivity\_table\_update (prev\_hop\_addr ,
69      OPC\_FALSE);
70
71  /* Update the route to the previous hop of the */
72  /* route request message. */
73  aodv\_rte\_route\_table\_entry\_update (ip\_dgram\_fd\_ptr ,
74      intf\_ici\_fdstruct\_ptr , tlv\_options\_ptr);
75
76  /* If the source address of the route request */
77  /* belongs to this node, then discard the IP */
78  /* datagram as it has received its own packet */

```

```

70  if (manet\_rte\_address\_belongs\_to\_node (module\_data\_ptr ,
71      rreq\_option\_ptr->src\_addr) == OPC\_TRUE)
72      {
73          if ((op\_prg\_odb\_ltrace\_active ("trace\_rreq") == OPC\_TRUE) ||
74              LTRACE\_ACTIVE)
75              {
76                  op\_prg\_odb\_print\_major (pid\_string , "Destroying the Route
77                      Request",
78                      "as the source node received its own packet", OPC\_NIL);
79              }
80
81              /* The originator of the route request has */
82              /* received its own packet again. Discard */
83              /* this IP datagram */
84              manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
85              op\_pk\_destroy (aadv\_pkptr);
86
87              FOUT;
88              }
89
90          /* Check to see if this node has received a RREQ */
91          /* with the same request ID and originator address */
92          if (aadv\_route\_request\_forward\_entry\_exists
93              (request\_table\_ptr , rreq\_option\_ptr->rreq\_id ,
94              rreq\_option\_ptr->src\_addr) == OPC\_TRUE)
95          {
96              /* A route request with the same request ID has */
97              /* already been received. Discard the packet */
98
99              if ((op\_prg\_odb\_ltrace\_active ("trace\_rreq") == OPC\_TRUE) ||
100                  LTRACE\_ACTIVE)
101              {
102                  op\_prg\_odb\_print\_major (pid\_string , "Destroying the Route
103                      Request",
104                      "as same request ID has already been received", OPC\_NIL);
105              }
106
107              manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
108              op\_pk\_destroy (aadv\_pkptr);
109
110              FOUT;
111              }
112
113          /* Insert the route request in the request table */
114          aadv\_request\_table\_forward\_rreq\_insert (request\_table\_ptr ,
115              rreq\_option\_ptr->rreq\_id , rreq\_option\_ptr->src\_addr);
116
117          /* This is a new route request packet that has not */
118          /* been received by this node before. Increment the */
119          /* hop count by one to account for the new hop */

```



```

114   rreq\_option\_ptr->hop\_count++;
115
116   /* Drop the rreq if it has reached network diameter */
117   if (rreq\_option\_ptr->hop\_count > net\_diameter )
118   {
119       /* Destroy the RREQ message */
120       op\_pk\_destroy (aadv\_pkptr);
121       manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
122
123       FOUT;
124   }
125
126   /* Calculate the lifetime for the route entry */
127   min\_lifetime = ((2.0 * net\_traversal\_time) - (2.0 *
        rreq\_option\_ptr->hop\_count * node\_traversal\_time));
128
129   /* Calculate the actual trust value of the RREQ packets */
130   actrust\_value = rreq\_option\_ptr->act\_trust *= node\_trust\_value;
131
132   /* Check if there exists a reverse route to the */
133   /* source node of the route request. */
134   route\_entry\_ptr = aadv\_route\_table\_entry\_get
        (route\_table\_ptr, rreq\_option\_ptr->src\_addr);
135
136   /* Get the interface\_info of the interface specified */
137   iface\_elem\_ptr = inet\_rte\_intf\_tbl\_access (module\_data\_ptr,
        intf\_ici\_fdstruct\_ptr->intf\_recvd\_index);
138
139   /* Create the corresponding port information accordingly */
140   /* with the IP family address. */
141   if (inet\_address\_family\_get (rreq\_option\_ptr->src\_addr) ==
        InetC\_Addr\_Family\_v4)
142   {
143       /* Get the port information for the IPv4 case. */
144       in\_port\_info = ip\_rte\_port\_info\_create
        (intf\_ici\_fdstruct\_ptr->intf\_recvd\_index,
        iface\_elem\_ptr->full\_name);
145
146       /* Get subnet mask for the IPv4 case. */
147       selected\_subnet\_mask = subnet\_mask;
148   }
149   else
150   {
151       /* Get the port information for the IPv6 case. */
152       in\_port\_info = ipv6\_rte\_port\_info\_create (module\_data\_ptr,
        intf\_ici\_fdstruct\_ptr->intf\_recvd\_index);
153
154       /* Get subnet mask for the IPv6 case. */
155       selected\_subnet\_mask = subnet\_mask\_ipv6;
156   }
157

```

```

158 if (route\_entry\_ptr == OPC\_NIL)
159 {
160     /* First get the trust information for the route entry */
161     nodetrust\_value = node\_trust\_value;
162     printf ("nodetrust\_value = %f\n", nodetrust\_value);
163
164     pathtrust\_value = actrust\_value;
165     printf ("pathtrust\_value = %f\n", pathtrust\_value);
166     /* No entry exists to the source of the route */
167     /* request. Create a new route entry */
168     route\_entry\_ptr = aodv\_route\_table\_entry\_create
        (route\_table\_ptr, rreq\_option\_ptr->src\_addr,
        selected\_subnet\_mask, prev\_hop\_addr,
169         in\_port\_info,
        rreq\_option\_ptr->hop\_count,
        rreq\_option\_ptr->src\_seq\_num,
        min\_lifetime, nodetrust\_value,
        pathtrust\_value);
170
171     route\_entry\_ptr->path\_trust = pathtrust\_value;
172
173     /* Send all packets queued to this destination */
174     aodv\_rte\_all\_pkts\_to\_dest\_send (rreq\_option\_ptr->src\_addr,
        route\_entry\_ptr, OPC\_FALSE);
175
176 }
177 else if( (rreq\_option\_ptr->src\_seq\_num >
        route\_entry\_ptr->dest\_seq\_num) and
        (rreq\_option\_ptr->act\_trust > route\_entry\_ptr->path\_trust)
        ||
178     ((rreq\_option\_ptr->src\_seq\_num ==
        route\_entry\_ptr->dest\_seq\_num) and
        (rreq\_option\_ptr->hop\_count <
        route\_entry\_ptr->hop\_count)) ||
179     ((rreq\_option\_ptr->src\_seq\_num ==
        route\_entry\_ptr->dest\_seq\_num) and
        (rreq\_option\_ptr->act\_trust >
        route\_entry\_ptr->path\_trust)) ||
180     ((rreq\_option\_ptr->src\_seq\_num ==
        route\_entry\_ptr->dest\_seq\_num) and
        (route\_entry\_ptr->route\_entry\_state ==
        AodvC\_Invalid\_Route)))
181 {
182     /* Update the route table entry if */
183     /* 1. We have invalid dest seq number */
184     /* 2. The new seq number is greater */
185     /* 3. Seq numbers are same and */
186     /* new hop count is smaller or */
187     /* we have invalid route entry */
188

```

```

189  if ((op\_prg\_odb\_ltrace\_active ("trace\_rreq") == OPC\_TRUE) ||
190      LTRACE\_ACTIVE)
191  {
192      printf("Route entry already exists: Old dest\_seq\_num: %d, Old
193          Hop Cnt: %d\n",
194          route\_entry\_ptr->dest\_seq\_num,
195          route\_entry\_ptr->hop\_count);
196      printf("Route entry already exists: new dest\_seq\_num: %d, new
197          Hop Cnt: %d\n",
198          rreq\_option\_ptr->src\_seq\_num,
199          rreq\_option\_ptr->hop\_count);
200      printf("Route entry already exists: act\_trust: %f, path\_trust:
201          %f\n",
202          rreq\_option\_ptr->act\_trust, route\_entry\_ptr->path\_trust);
203      op\_prg\_odb\_print\_major (pid\_string, "Updating route table
204          with new RREQ", OPC\_NIL);
205  }
206
207  /* Update the sequence number */
208  route\_entry\_ptr->dest\_seq\_num =
209      rreq\_option\_ptr->src\_seq\_num;
210
211  /* Update the path trust value */
212  route\_entry\_ptr->path\_trust = rreq\_option\_ptr->act\_trust;
213  printf ("path\_trust = %f\n", route\_entry\_ptr->path\_trust);
214
215  /* Do this before adding info to IP Cmn table in case route was
216      invalid */
217  route\_entry\_ptr->hop\_count = rreq\_option\_ptr->hop\_count;
218  route\_entry\_ptr->next\_hop\_port\_info = in\_port\_info;
219
220  if (!inet\_address\_equal (route\_entry\_ptr->next\_hop\_addr,
221      prev\_hop\_addr))
222  {
223      /* Update the route table entry */
224      aodv\_route\_table\_entry\_next\_hop\_update (route\_table\_ptr,
225          route\_entry\_ptr,
226          inet\_address\_copy (prev\_hop\_addr),
227          rreq\_option\_ptr->hop\_count, in\_port\_info);
228  }
229
230  if (route\_entry\_ptr->route\_entry\_state != AodvC\_Invalid\_Route)
231  {
232      existing\_lifetime = route\_entry\_ptr->route\_expiry\_time -
233          op\_sim\_time ();
234      lifetime = aodv\_rte\_max\_find (existing\_lifetime,
235          min\_lifetime);
236  }
237  else

```

```

226     {
227     lifetime = min\_lifetime;
228     aadv\_route\_table\_entry\_state\_set (route\_table\_ptr,
        route\_entry\_ptr, rreq\_option\_ptr->src\_addr,
        AadvC\_Valid\_Route);
229     }
230
231     /* Set the valid sequence number field to true */
232     route\_entry\_ptr->valid\_dest\_sequence\_number\_flag = OPC\_TRUE;
233
234     aadv\_route\_table\_entry\_expiry\_time\_update (route\_entry\_ptr,
        rreq\_option\_ptr->src\_addr, lifetime,
        AODVC\_ROUTE\_ENTRY\_INVALID);
235     }
236
237     else if( !inet\_address\_equal (route\_entry\_ptr->next\_hop\_addr,
        prev\_hop\_addr))
238     {
239     /* Drop the route request, if the nexthop on reverse path */
240     /* is different from the previous hop. This is to avoid */
241     /* loop formation in certain cases */
242     /* Destroy the RREQ message */
243     op\_pk\_destroy (aadv\_pkptr);
244     manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
245
246     FOUT;
247     }
248
249 % This function is used to handle the RREP packets
250 Function static void
251 aadv\_rte\_rrep\_pkt\_arrival\_handle (Packet* ip\_pkptr, Packet*
        aadv\_pkptr, IpT\_Dgram\_Fields* ip\_dgram\_fd\_ptr,
252     IpT\_Rte\_Ind\_Ici\_Fields* intf\_ici\_fdstruct\_ptr,
        AadvT\_Packet\_Option* tlv\_options\_ptr)
253     {
254     AadvT\_Rrep*      rrep\_option\_ptr;
255     InetT\_Address    prev\_hop\_addr;
256     InetT\_Address    next\_hop\_addr;
257     IpT\_Interface\_Info* iface\_elem\_ptr;
258     IpT\_Port\_Info    in\_port\_info;
259     AadvT\_Route\_Entry* route\_entry\_ptr = OPC\_NIL;
260     Boolean           route\_updated = OPC\_FALSE;
261     Boolean           reached\_src = OPC\_FALSE;
262     int               dest\_seq\_num;
263     int               hop\_count;
264     double            nodetrust\_value, pathtrust\_value;
265     AadvC\_Route\_Entry\_State route\_entry\_state;
266     Packet*           ip\_rrep\_pkptr;
267     char               src\_node\_name [OMSC\_HNAME\_MAX\_LEN];
268     char               src\_hop\_addr\_str [INETC\_ADDR\_STR\_LEN];
269     char               dest\_node\_name [OMSC\_HNAME\_MAX\_LEN];

```

```

270 char          dest\_hop\_addr\_str [INETC\_ADDR\_STR\_LEN];
271 char          temp\_str [2048], temp\_str1 [2048];
272 char          next\_addr\_str [INETC\_ADDR\_STR\_LEN];
273 char          next\_node\_name [OMSC\_HNAME\_MAX\_LEN];
274 char          dest\_addr\_str [INETC\_ADDR\_STR\_LEN];
275 double        existing\_lifetime, lifetime;
276 double        route\_expiry\_time;
277 ManetT\_Nexthop\_Info* manet\_nexthop\_info\_ptr = OPC\_NIL;
278 AodvT\_Route\_Entry* fwd\_path\_entry\_ptr = OPC\_NIL;
279 InetT\_Subnet\_Mask selected\_subnet\_mask;
280
281 /** Handles the arrival of the route reply message **/
282 FIN (aodv\_rte\_rrep\_pkt\_arrival\_handle (<args>));
283
284 /* A route reply packet has arrived at this node */
285 /* Get the reply options from the packet */
286 rrep\_option\_ptr = (AodvT\_Rrep*) tlv\_options\_ptr->value\_ptr;
287
288 /* Get the previous hop from which this packet arrived */
289 prev\_hop\_addr = ip\_dgram\_fd\_ptr->src\_addr;
290
291 /* Calculate the actual trust value when RREP packet arrived */
292 rrep\_option\_ptr->act\_trust *= node\_trust\_value;
293
294 /* Check if node has received its own route reply */
295 if (manet\_rte\_address\_belongs\_to\_node (module\_data\_ptr,
    rrep\_option\_ptr->dest\_addr))
296 {
297     /* Drop the route reply */
298     op\_pk\_destroy (aodv\_pkptr);
299     manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
300
301     FOUT;
302 }
303
304 /* Update the connectivity table */
305 aodv\_rte\_neighbor\_connectivity\_table\_update (prev\_hop\_addr,
    OPC\_FALSE);
306
307 /* Update the route to the previous hop of the */
308 /* route reply message. */
309 aodv\_rte\_route\_table\_entry\_update (ip\_dgram\_fd\_ptr,
    intf\_ici\_fdstruct\_ptr, tlv\_options\_ptr);
310
311 if (LTRACE\_ACTIVE)
312 {
313     inet\_address\_print (src\_hop\_addr\_str,
        ip\_dgram\_fd\_ptr->src\_addr);
314     inet\_address\_to\_hname (ip\_dgram\_fd\_ptr->src\_addr,
        src\_node\_name);

```

```

315     inet\_address\_print (dest\_hop\_addr\_str ,
316         rrep\_option\_ptr->dest\_addr);
317     inet\_address\_to\_hname (rrep\_option\_ptr->dest\_addr ,
318         dest\_node\_name);
319     sprintf (temp\_str , "from node %s (%s). Originator of this RREP: %s
320         (%s)" ,
321         src\_hop\_addr\_str , src\_node\_name , dest\_hop\_addr\_str ,
322         dest\_node\_name);
323     op\_prg\_odb\_print\_major (pid\_string , "Received a route reply
324         packet" , temp\_str , OPC\_NIL);
325 }
326
327 /* Increment the hop count by one to account */
328 /* for the new hop through the intermediate node */
329 rrep\_option\_ptr->hop\_count++;
330
331 /* Drop the rreq if it has reached network diameter */
332 if (rrep\_option\_ptr->hop\_count > net\_diameter )
333 {
334     /* Destroy the RREQ message */
335     op\_pk\_destroy (aodv\_pkptr);
336     manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
337
338     FOUT;
339 }
340
341 /* Get the interface\_info of the interface specified */
342 iface\_elem\_ptr = inet\_rte\_intf\_tbl\_access (module\_data\_ptr ,
343     intf\_ici\_fdstruct\_ptr->intf\_recvd\_index);
344
345 /* Check for the IP address family. */
346 if (inet\_address\_family\_get (rrep\_option\_ptr->dest\_addr) ==
347     InetC\_Addr\_Family\_v4)
348 {
349     /* Get the port information for the IPv4 case. */
350     in\_port\_info = ip\_rte\_port\_info\_create
351         (intf\_ici\_fdstruct\_ptr->intf\_recvd\_index ,
352         iface\_elem\_ptr->full\_name);
353
354     /* Get subnet mask for the IPv4 case. */
355     selected\_subnet\_mask = subnet\_mask;
356 }
357 else
358 {
359     /* Get the port information for the IPv6 case. */
360     in\_port\_info = ipv6\_rte\_port\_info\_create (module\_data\_ptr ,
361         intf\_ici\_fdstruct\_ptr->intf\_recvd\_index);
362
363     /* Get subnet mask for the IPv6 case. */
364     selected\_subnet\_mask = subnet\_mask\_ipv6;
365 }

```

```

356
357  /* Check if this is the final destination of the RREP message */
358  reached\_src = manet\_rte\_address\_belongs\_to\_node
      (module\_data\_ptr, rrep\_option\_ptr->src\_addr);
359
360  /* Check if the route exists to the destination IP */
361  /* address in the RREP message. */
362  route\_entry\_ptr = aadv\_route\_table\_entry\_get
      (route\_table\_ptr, rrep\_option\_ptr->dest\_addr);
363  if(route\_entry\_ptr == OPC\_NIL)
364  {
365      /* First get the trust information for route entry */
366      nodetrust\_value = node\_trust\_value;
367      printf ("node\_trust\_value = %f\n", nodetrust\_value);
368
369      pathtrust\_value = rrep\_option\_ptr->act\_trust *
          node\_trust\_value;
370      printf ("pathtrust\_value = %f\n", pathtrust\_value);
371      /* No route exists to this destination */
372      /* Create a new route table entry */
373      route\_entry\_ptr = aadv\_route\_table\_entry\_create
          (route\_table\_ptr, rrep\_option\_ptr->dest\_addr,
          selected\_subnet\_mask, ip\_dgram\_fd\_ptr->src\_addr,
374          in\_port\_info, rrep\_option\_ptr->hop\_count,
          rrep\_option\_ptr->dest\_seq\_num,
375          rrep\_option\_ptr->lifetime, nodetrust\_value,
          pathtrust\_value);
376
377      /* Send all packets queued to this destination */
378      aadv\_rte\_all\_pkts\_to\_dest\_send
          (rrep\_option\_ptr->dest\_addr, route\_entry\_ptr,
          reached\_src);
379
380      /* Indicate that the route has been created */
381      route\_updated = OPC\_TRUE;
382  }
383  else
384  {
385      /* A route does exist to this destination. Update the */
386      /* route table entry if : */
387      /* (a) the sequence number is invalid in the route */
388      /* table entry */
389      /* (b) the destination sequence number in the RREP is */
390      /* greater than node's copy of the sequence number */
391      /* (c) the sequence numbers are the same but the route */
392      /* is marked as inactive */
393      /* (d) the sequence numbers are the same, and the new */
394      /* hop count is smaller than the hop count in the */
395      /* route table entry. */
396
397      dest\_seq\_num = route\_entry\_ptr->dest\_seq\_num;

```

```

398 hop\_count = route\_entry\_ptr->hop\_count;
399 pathtrust\_value = route\_entry\_ptr->path\_trust;
400 route\_entry\_state = route\_entry\_ptr->route\_entry\_state;
401
402
403 if ((op\_prg\_odb\_ltrace\_active ("trace\_rrep") == OPC\_TRUE) ||
    LTRACE\_ACTIVE)
404 {
405     printf ("Route already Exists: DestSeq: %d, HopCnt:%d \n",
406             dest\_seq\_num, hop\_count);
407     printf ("                NewDestSeq: %d, NewHopCnt: %d \n",
408             rrep\_option\_ptr->dest\_seq\_num,
409             rrep\_option\_ptr->hop\_count);
410 }
411 if (((rrep\_option\_ptr->dest\_seq\_num > dest\_seq\_num) ||
412      ((rrep\_option\_ptr->dest\_seq\_num > dest\_seq\_num) and
413       (rrep\_option\_ptr->act\_trust > pathtrust\_value)) ||
414      ((rrep\_option\_ptr->dest\_seq\_num == dest\_seq\_num) and
415       (route\_entry\_state == AodvC\_Invalid\_Route)) ||
416      ((rrep\_option\_ptr->dest\_seq\_num == dest\_seq\_num) and
417       (rrep\_option\_ptr->act\_trust > pathtrust\_value)) ||
418      ((rrep\_option\_ptr->dest\_seq\_num == dest\_seq\_num) and
419       (rrep\_option\_ptr->hop\_count < hop\_count))))
420 {
421     /* Update the route table entry if */
422     /* We have invalid dest seq number, or new seq */
423     /* number is greater or if seq numbers are same */
424     /* new hop count is greater or we have invalid */
425     /* route entry */
426
427     if ((op\_prg\_odb\_ltrace\_active ("trace\_rrep") == OPC\_TRUE)
428         || LTRACE\_ACTIVE)
429     {
430         op\_prg\_odb\_print\_major (pid\_string, " Updating Route Table
431         with new RREP", OPC\_NIL);
432     }
433
434     /* Do this before adding info to IP Cmn table in case route was
435        invalid */
436     route\_entry\_ptr->hop\_count = rrep\_option\_ptr->hop\_count;
437     route\_entry\_ptr->path\_trust = rrep\_option\_ptr->act\_trust;
438     route\_entry\_ptr->next\_hop\_port\_info = in\_port\_info;
439
440     if (!inet\_address\_equal (route\_entry\_ptr->next\_hop\_addr,
441                             prev\_hop\_addr))
442     {
443         /* Update the next hop and the hop count to the new value */
444         aodv\_route\_table\_entry\_next\_hop\_update
445             (route\_table\_ptr, route\_entry\_ptr,

```



```

437             inet\_address\_copy (prev\_hop\_addr) ,
438                 rrep\_option\_ptr->hop\_count ,
439                 in\_port\_info);
440     }
441     /* Set the route to be a valid route */
442     if (route\_entry\_state != AodvC\_Valid\_Route)
443     {
444         aodv\_route\_table\_entry\_state\_set (route\_table\_ptr ,
445             route\_entry\_ptr , rrep\_option\_ptr->dest\_addr ,
446             AodvC\_Valid\_Route);
447     }
448     /* Mark the destination sequence as valid */
449     aodv\_route\_table\_entry\_param\_set (route\_entry\_ptr ,
450         AODVC\_ROUTE\_ENTRY\_VALID\_SEQ\_NUM\_FLAG, OPC\_TRUE);
451     /* Set the destination sequence number to that in the RREP
452        message */
453     aodv\_route\_table\_entry\_param\_set (route\_entry\_ptr ,
454         AODVC\_ROUTE\_ENTRY\_DEST\_SEQ\_NUM,
455         rrep\_option\_ptr->dest\_seq\_num);
456     /* Set the expiry time to be the current time */
457     /* plus the lifetime of the RREP message */
458     aodv\_route\_table\_entry\_expiry\_time\_update
459         (route\_entry\_ptr , rrep\_option\_ptr->dest\_addr ,
460         rrep\_option\_ptr->lifetime ,
461         AODVC\_ROUTE\_ENTRY\_INVALID);
462     /* Send all packets queued to this destination */
463     aodv\_rte\_all\_pkts\_to\_dest\_send
464         (rrep\_option\_ptr->dest\_addr , route\_entry\_ptr ,
465         reached\_src);
466     /* Indicate that the route has been created */
467     route\_updated = OPC\_TRUE;
468     }
469     }
470     if (reached\_src)
471     {
472         /* This is the destination of the RREP message */
473         /* Check if the destination was under local */
474         /* repair and if so remove it from the list */
475         if (aodv\_rte\_local\_repair\_exists
476             (rrep\_option\_ptr->dest\_addr , OPC\_TRUE) == OPC\_TRUE)
477         {
478             /* This destination was under local repair */
479             /* An RREP has been received for the */
480             /* desired destination. Compare the hop */

```

```

475      /* count of the new route with that of the */
476      /* invalid route table entry */
477      aadv\route\_table\_entry\_param\_get (route\_entry\_ptr,
        AODVC\ROUTE\ENTRY\HOP\COUNT, hop\_count);
478
479      if (rrep\_option\_ptr->hop\_count > hop\_count)
480      {
481          /* If new determined route has greater */
482          /* hopcount, issue a route error message */
483          /* for the destination with the N bit set. */
484
485          if (LTRACE\_ACTIVE)
486          {
487              op\_prg\_odb\_print\_major (pid\_string, "This node underlocal
                repair and RREP \
488              received with less hopcount so RERR", OPC\_NIL);
489          }
490          aadv\rte\_route\_error\_process
            (rrep\_option\_ptr->dest\_addr, route\_entry\_ptr, OPC\_NIL,
491            AodvC\_Data\_Packet\_No\_Route, OPC\_TRUE);
492          aadv\_packet\_queue\_all\_pkts\_to\_dest\_delete
            (pkt\_queue\_ptr, rrep\_option\_ptr->dest\_addr);
493      }
494  }
495
496  /* Cancel the route request timer for this */
497  /* request ID that we have received a RREP */
498  aadv\_route\_request\_orig\_entry\_delete (request\_table\_ptr,
        rrep\_option\_ptr->dest\_addr);
499  op\_pk\_destroy (aadv\_pkptr);
500  manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
501
502  FOUT;
503  }
504
505  /* We are going to forward this route reply */
506  if(((fwd\_path\_entry\_ptr = aadv\_route\_table\_entry\_get
        (route\_table\_ptr, rrep\_option\_ptr->src\_addr)) != OPC\_NIL)
507    and (fwd\_path\_entry\_ptr->route\_entry\_state !=
        AodvC\_Invalid\_Route))
508  {
509      /* Forward the route reply, if we have route entry for the */
510      /* originator of RREQ i.e. the source address field in RREP pkt. */
511      /* Access the next hop address from the route entry */
512      next\_hop\_addr = fwd\_path\_entry\_ptr->next\_hop\_addr;
513      hop\_count = fwd\_path\_entry\_ptr->hop\_count;
514      route\_expiry\_time = fwd\_path\_entry\_ptr->route\_expiry\_time;
515
516      /* Update the reverse path expiry time before sending out the RREP */
517      /*

```

```

517     existing\_lifetime = route\_expiry\_time - op\_sim\_time();
518
519     /* Since active\_route\_timeout = my\_route\_timeout/2, using this
       according to RFC */
520     lifetime = aodv\_rte\_max\_find (existing\_lifetime ,
       my\_route\_timeout/2);
521     aodv\_route\_table\_entry\_expiry\_time\_update
       (fwd\_path\_entry\_ptr, rrep\_option\_ptr->src\_addr, lifetime ,
       AODVC\_ROUTE\_ENTRY\_INVALID);
522
523     /* Set the ack requested flag for this node */
524     rrep\_option\_ptr->ack\_required\_flag = ack\_required;
525
526     /* Update the precursor list */
527     aodv\_route\_table\_precursor\_add (fwd\_path\_entry\_ptr ,
       prev\_hop\_addr);
528     aodv\_route\_table\_precursor\_add (route\_entry\_ptr ,
       next\_hop\_addr);
529
530     /* Allocate memory for manet\_nexthop\_info\_ptr */
531     manet\_nexthop\_info\_ptr = (ManetT\_Nexthop\_Info *)
       op\_prg\_mem\_alloc (sizeof (ManetT\_Nexthop\_Info));
532
533     /* Encapsulate the AODV packet in a new IP datagram */
534     ip\_rrep\_pkptr = aodv\_rte\_ip\_datagram\_create (aodv\_pkptr ,
       rrep\_option\_ptr->src\_addr, fwd\_path\_entry\_ptr ,
535     IPC\_DEFAULT\_TTL, next\_hop\_addr, manet\_nexthop\_info\_ptr);
536
537     /* Update the statistics for the routing traffic sent */
538     aodv\_support\_routing\_traffic\_sent\_stats\_update
       (local\_stat\_handle\_ptr, global\_stat\_handle\_ptr ,
       ip\_rrep\_pkptr);
539
540     if (LTRACE\_ACTIVE)
541     {
542         inet\_address\_print (next\_addr\_str, next\_hop\_addr);
543         inet\_address\_to\_hname (next\_hop\_addr, next\_node\_name);
544         inet\_address\_print (dest\_addr\_str ,
       rrep\_option\_ptr->src\_addr);
545         inet\_address\_to\_hname (rrep\_option\_ptr->src\_addr ,
       dest\_node\_name);
546         sprintf (temp\_str, "Forwarding the route reply to next hop %s
       (%s)", next\_addr\_str, next\_node\_name);
547         sprintf (temp\_str1, " destined to %s(%s)", dest\_addr\_str ,
       dest\_node\_name);
548         op\_prg\_odb\_print\_major (pid\_string, temp\_str, temp\_str1 ,
       OPC\_NIL);
549     }
550
551     /* Install the event state */

```

```

552      /* This event will be processed in ip\_rte\_support.ex.c while
        receiving */
553      /* AODV control packets. manet\_nexthop\_info\_ptr will point to
        structure */
554      /* containing nexthop info, so IP table lookup is not again done
        for them. */
555      op\_ev\_state\_install (manet\_nexthop\_info\_ptr, OPC\_NIL);
556
557      /* Send the packet to the CPU */
558      manet\_rte\_to\_cpu\_pkt\_send\_schedule (module\_data\_ptr,
        parent\_prohandle, parent\_pro\_id, ip\_rrep\_pkptr);
559      op\_ev\_state\_install (OPC\_NIL, OPC\_NIL);
560
561      /* Destory the old IP packet */
562      manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
563
564      FOUT;
565      }
566      else
567      {
568          /* We do not have route entry to forward this */
569          /* route reply. Discard it. */
570          op\_pk\_destroy (aodv\_pkptr);
571          manet\_rte\_ip\_pkt\_destroy (ip\_pkptr);
572
573          FOUT;
574      }
575      }
576
577      % This function is used to handle and update the route entry of RREQ
        and RREP packets
578      Funtion static void
579      aodv\_rte\_route\_table\_entry\_update (IpT\_Dgram\_Fields*
        ip\_dgram\_fd\_ptr, IpT\_Rte\_Ind\_Ici\_Fields*
        intf\_ici\_fdstruct\_ptr,
580          AodvT\_Packet\_Option* tlv\_options\_ptr)
581      {
582          InetT\_Address      prev\_hop\_addr;
583          AodvT\_Route\_Entry* route\_entry\_ptr;
584          IpT\_Interface\_Info* iface\_elem\_ptr;
585          IpT\_Port\_Info      in\_port\_info;
586          AodvT\_Rreq*          rreq\_option\_ptr;
587          AodvT\_Rrep*          rrep\_option\_ptr;
588          int                  sequence\_num, dest\_seq\_num;
589          int                  hop\_count;
590          double               lifetime;
591          double               actrust\_value;
592          double               nodetrust\_value, pathtrust\_value;
593          Boolean              reached\_src = OPC\_FALSE;
594          AodvC\_Route\_Entry\_State route\_entry\_state;
595          InetT\_Subnet\_Mask      selected\_subnet\_mask;

```

```

596 Boolean      hello\_msg = OPC\_FALSE;
597
598 /** Creates or updates the route entry to the */
599 /** previous hop from which the control packet */
600 /** was received. */
601 FIN (aodv\_rte\_route\_table\_entry\_update (<args>));
602
603 /* Get the previous hop from which this packet arrived */
604 prev\_hop\_addr = ip\_dgram\_fd\_ptr->src\_addr;
605
606 switch (tlv\_options\_ptr->type)
607 {
608     case (AODVC\_ROUTE\_REQUEST):
609     {
610         rreq\_option\_ptr = (AodvT\_Rreq*) tlv\_options\_ptr->value\_ptr;
611
612         /* Check if the source address is the previous hop */
613         if (inet\_address\_equal (prev\_hop\_addr,
614             rreq\_option\_ptr->src\_addr))
615         {
616             /* Get the source sequence number */
617             sequence\_num = rreq\_option\_ptr->src\_seq\_num;
618         }
619         else
620         {
621             /* Set the sequence number as invalid as it */
622             /* is not known by the RREQ message */
623             sequence\_num = AODVC\_DEST\_SEQ\_NUM\_INVALID;
624         }
625
626         /* Initialize the lifetime to active route timeout */
627         lifetime = route\_table\_ptr->route\_expiry\_time;
628
629         /* Get the actual trust value */
630         actrust\_value = rreq\_option\_ptr->act\_trust *
631             node\_trust\_value;
632         printf ("actrust\_value = %f\n", actrust\_value);
633
634         break;
635     }
636
637     case (AODVC\_ROUTE\_REPLY):
638     {
639         rrep\_option\_ptr = (AodvT\_Rrep*) tlv\_options\_ptr->value\_ptr;
640
641         /* Check if the source address is the previous hop */
642         if (inet\_address\_equal (prev\_hop\_addr,
643             rrep\_option\_ptr->dest\_addr))
644         {
645             /* Get the source sequence number */

```

```

644     sequence\_num = rrep\_option\_ptr->dest\_seq\_num;
645     lifetime = rrep\_option\_ptr->lifetime;
646 }
647 else
648 {
649     /* Set the sequence number as invalid as it */
650     /* is not known by the RREP message */
651     sequence\_num = AODVC\_DEST\_SEQ\_NUM\_INVALID;
652     lifetime = route\_table\_ptr->route\_expiry\_time;
653 }
654
655     /* Check if this is the destination of the route reply */
656     reached\_src = manet\_rte\_address\_belongs\_to\_node
        (module\_data\_ptr, rrep\_option\_ptr->src\_addr);
657
658     /* Get the actual trust value */
659     actrust\_value = rrep\_option\_ptr->act\_trust *
        node\_trust\_value;
660     printf ("actrust\_value = %f\n", actrust\_value);
661
662     break;
663 }
664
665 case (AODVC\_HELLO):
666 {
667     rrep\_option\_ptr = (AodvT\_Rrep*) tlv\_options\_ptr->value\_ptr;
668     sequence\_num = rrep\_option\_ptr->dest\_seq\_num;
669     lifetime = rrep\_option\_ptr->lifetime;
670     reached\_src = OPC\_TRUE;
671     hello\_msg = OPC\_TRUE;
672
673     break;
674 }
675 }
676
677 /* Check if an route entry exists to the previous hop */
678 route\_entry\_ptr = aodv\_route\_table\_entry\_get
        (route\_table\_ptr, prev\_hop\_addr);
679
680 /* Get the interface\_info of the interface specified */
681 iface\_elem\_ptr = inet\_rte\_intf\_tbl\_access (module\_data\_ptr,
        intf\_ici\_fdstruct\_ptr->intf\_recvd\_index);
682
683 /* Check for IP address family. */
684 if (inet\_address\_family\_get (prev\_hop\_addr) ==
        InetC\_Addr\_Family\_v4)
685 {
686     /* Get the port information for the IPv4 case. */
687     in\_port\_info = ip\_rte\_port\_info\_create
        (intf\_ici\_fdstruct\_ptr->intf\_recvd\_index,
        iface\_elem\_ptr->full\_name);

```

```

688
689      /* Get subnet mask for the IPv4 case.          */
690      selected\_subnet\_mask = subnet\_mask;
691  }
692  else
693  {
694      /* Get the port information for the IPv6 case.    */
695      in\_port\_info = ipv6\_rte\_port\_info\_create (module\_data\_ptr ,
        intf\_ici\_fdstruct\_ptr->intf\_recvd\_index);
696
697      /* Get subnet mask for the IPv6 case.          */
698      selected\_subnet\_mask = subnet\_mask\_ipv6;
699  }
700
701  if (route\_entry\_ptr == OPC\_NIL)
702  {
703      /* First get the trust information */
704      nodetrust\_value = node\_trust\_value;
705      printf ("nodetrust\_value = %f\n", nodetrust\_value);
706
707      pathtrust\_value = actrust\_value;
708      printf ("pathtrust\_value = %f\n", pathtrust\_value);
709      /* No route exists to the previous hop */
710      /* Create a new route entry          */
711      route\_entry\_ptr = aadv\_route\_table\_entry\_create
        (route\_table\_ptr, prev\_hop\_addr, selected\_subnet\_mask,
        prev\_hop\_addr, in\_port\_info,
712          1, sequence\_num, lifetime ,
        nodetrust\_value , pathtrust\_value);
713
714      /* Get the path trust value */
715      route\_entry\_ptr->path\_trust = pathtrust\_value;
716
717      /* Send all packets queued to this destination */
718      aadv\_rte\_all\_pkts\_to\_dest\_send (prev\_hop\_addr ,
        route\_entry\_ptr, reached\_src);
719  }
720  else
721  {
722      /* There exists an entry to this destination */
723      /* Update the entry in the route table if the */
724      /* new sequence number is either :          */
725      /* (a) higher than the destination sequence */
726      /*      number in the route table, or      */
727      /* (b) the sequence numbers are equal, but the */
728      /*      hop count plus one of the new info is */
729      /*      smaller than the existing hop count, or */
730      /* (c) seq number are equal but my route entry */
731      /*      is invalid.                          */
732      /* (d) the sequence number is unknown      */
733

```

```

734 dest\_seq\_num = route\_entry\_ptr->dest\_seq\_num;
735 hop\_count = route\_entry\_ptr->hop\_count;
736 pathtrust\_value = route\_entry\_ptr->path\_trust;
737 route\_entry\_state = route\_entry\_ptr->route\_entry\_state;
738
739
740 /* Update the route entry if the received packet has higher dest
    seq no */
741 /* or same seq no with better hop count or my route entry is
    invalid */
742 /* In case of hello message, always update the route entry */
743
744 if ((hello\_msg) ||
745     (sequence\_num > dest\_seq\_num) and (actrust\_value >
        pathtrust\_value) ||
746     ((sequence\_num == dest\_seq\_num) and (route\_entry\_state ==
        AodvC\_Invalid\_Route)) ||
747     ((sequence\_num == dest\_seq\_num) and (actrust\_value >
        pathtrust\_value)) ||
748     ((sequence\_num == dest\_seq\_num) and (hop\_count < 2)))
749 {
750
751     /* Do this before adding info to IP Cmn table in case route was
        invalid */
752     route\_entry\_ptr->dest\_seq\_num = sequence\_num;
753     pathtrust\_value = actrust\_value;
754     printf ( "pathtrust\_value %f\n", pathtrust\_value);
755     route\_entry\_ptr->hop\_count = 1;
756     route\_entry\_ptr->next\_hop\_port\_info = in\_port\_info;
757
758     if (!inet\_address\_equal (route\_entry\_ptr->next\_hop\_addr,
        prev\_hop\_addr))
759     {
760         /* Update the next hop and the hop count to the new value */
761         aodv\_route\_table\_entry\_next\_hop\_update
            (route\_table\_ptr, route\_entry\_ptr,
762             inet\_address\_copy (prev\_hop\_addr), 1,
            in\_port\_info);
763     }
764
765     if((route\_entry\_state == AodvC\_Invalid\_Route))
766     {
767         /* If Route was invalid, make it Valid, and add this to the IP
            Common table */
768         aodv\_route\_table\_entry\_state\_set (route\_table\_ptr,
            route\_entry\_ptr, prev\_hop\_addr, AodvC\_Valid\_Route);
769     }
770
771
772     if (sequence\_num == AODVC\_DEST\_SEQ\_NUM\_INVALID)

```



```

773         route\_entry\_ptr->valid\_dest\_sequence\_number\_flag =
              OPC\_FALSE;
774     else
775         route\_entry\_ptr->valid\_dest\_sequence\_number\_flag =
              OPC\_TRUE;
776
777     /* Update the expiry\_time of the route entry */
778     aodv\_route\_table\_entry\_expiry\_time\_update
        (route\_entry\_ptr, prev\_hop\_addr, lifetime,
          AODVC\_ROUTE\_ENTRY\_INVALID);
779     }
780 }
781
782 FOUT;
783 }

```